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SUMMARY OF LUBRICATION PROBLEMS IN VACUUM ENVIRONMENT

By Robert L. Johnson and William J. Anderson

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

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SUMMARY

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A cross section of the information available on lubrication in vacuum is presented to illustrate the problems and characteristics associated with various mechanical devices and materials.

Lubrication problems of mechanical devices operating in space are considered to result primarily from low pressure and oxygen deficiency of the environment. Lubricant films will evaporate, and when the underlying oxide films (on metals) are worn away, the nascent metals will weld. Metal transfer that results is so severe as to destroy operating tolerances in bearings and gears. Devices run at higher temperatures as a result of the vacuum environment than they do in air, since the heat dissipation problem is more difficult.

Operation of components in sealed units that have higher pressure than the surrounding environment is a practical solution to many problems. In many cases, however, devices must be exposed to space environment at pressures to 10^{-13} mm Hg and possibly lower. Polymers (e.g., Teflon), inorganic compounds (e.g., MoS_2), metallic films (e.g., solid gold and liquid gallium) can be effective lubricants and are used in various ways. Alloys that include

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film forming microconstituents and ceramic type materials can be useful for bearing surfaces.

Special design considerations are required, in many cases, for the satisfactory use of mechanical components in vacuum. Friction, wear, and adhesion problems are common to bearings, gears, electric contacts, and seals. Much fundamental information is being gained.

INTRODUCTION

Mechanical devices that require lubrication are common to most scientific satellite experiments and spacecraft. The information on lubrication in vacuum that is available to mechanical designers concerned with space equipment is inadequate. Thus, in the design stage, many laboratory tests of lubricated devices are conducted in vacuum chambers. An appreciation of the scope of present and anticipated problems is important to the planning of long range research and development studies on lubrication for space applications. Similarly, it is necessary to evaluate presently available information applicable to the problem of lubricating space equipment.

The objective of this report is to provide a summary of the status of technical information available for the solution of anticipated lubrication problems in the vacuum of outer space. Specific data are avoided in certain instances to protect proprietary interests.

Data available from the technical literature cannot provide timely or adequate coverage for this active but poorly defined problem area. To help resolve the program planning of the NASA efforts in this area, a survey was made among a number of organizations concerned with space equipment lubrication

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in the spring of 1961. Repeated contacts have been made thereafter with active groups in the field. These activities represent an effort to obtain a significant cross section of the information available in the problem area, which encompasses a broad spectrum of problems. Organizations contacted included contractors responsible for flight vehicles, systems, flight experiments, electronic equipment, primary and auxiliary powerplants, research and development laboratories, and contracting government organizations.

The Aerospace Lubrication Research Survey reported in December 1962 by the Lubricants Group for the Office of the Director of Defense Research and Engineering (ref. 1) provides a convenient tabulation of research projects. Organizations surveyed by the authors in obtaining the information reported herein were also subsequently contacted for contributions to reference 1.

SPACE SIMULATION

Pressures of interstellar space can be represented as extreme vacuum (10^{-19} to 10^{-25} mm Hg or lower, ref. 2), and pressures in the upper atmosphere of earth approach 10^{-13} mm Hg, as shown in figure 1 (ref. 3). The best vacuum claimed for laboratory equipment has been of the order of 10^{-15} mm Hg, and seldom are pressures lower than 10^{-10} mm Hg achieved. A common limit for good equipment has usually been 10^{-8} mm Hg, and the majority of experimental lubrication studies have been conducted at pressure in the region of 10^{-6} mm Hg. The pressure values mentioned for laboratory experience represent unverified extrapolations, where pressures below 10^{-6} mm Hg have been claimed because of uncertainties in the calibration of pressure-measuring devices. Carefully conceived flight and laboratory programs (with

apparatus developed by National Research Corporation) supported by NASA Goddard Space Flight Center were partly aimed at clarifying and extending limits of usefulness as well as calibration of pressure-measuring devices.

Several independent calculations based on the time necessary to develop a monomolecular film of oxygen on a surface (sticking coefficient λ of 1) suggest that pressures of 1×10^{-9} mm Hg, or lower, are required for lubrication experiments of significant duration (>1 hr). It should be emphasized that, in lubrication phenomena, oxygen has such a profound influence that a single molecular layer could render data of questionable value for extreme vacuum conditions. Figure 2 presents information showing that, with N_2 , O_2 , or air and a sticking coefficient λ of 1, a monolayer will form in the 10^{-5} to 10^{-6} mm Hg range in about 1 second. An additional factor is that, at the lower pressure, degassing of metals releases hydrogen. This hydrogen can be expected to combine chemically with the oxygen available to form H_2O and also to reduce surface oxides.

The matter in outer space include molecular and atomic species of gases in varied proportions. Atomic hydrogen is a predominant form of matter (ref. 3) at 600 miles and greater distance from the earth. Thus, it becomes important in space simulation not only to know the total pressure but to provide correct partial pressures of the predominant species of matter. Mass spectrometry measurements can be used to define more closely the species present and their partial pressures in laboratory experiments. Fortunately, scientific flight experiments include spectrometry analyses that will continue to provide better data on space conditions.

In laboratory vacuum systems, the method of pumping will cause great variations in species present in test chambers. Mass spectrometry measurements can resolve these relations. Ion-gettering pumps create ionized particles that are chemically active and thus contribute to compound formation. They have low pumping speeds for noble gases, and, under certain conditions, desorption of previously pumped gases can occur.

Oil-diffusion pumping is an economical method of achieving pressures as low as 10^{-10} mm Hg. Much of the friction and lubrication data obtained, however, are virtually worthless because of specimen contamination by back migration of diffusion-pump oil (ref. 4). Normally unlubricated bearings have been run for thousands of hours without failure in diffusion-pumped systems; under the same operating conditions in one instance, a bearing failure occurred in minutes when a different method of pumping was employed. A simple qualitative surface energy test has been used as a guide in NASA Lewis experiments to detect contamination. If metal surfaces are wetted by a drop of distilled water, they are considered clean; if the surface is not wetted by the distilled water, organic contamination is considered to be present. Such checks are made on specimen surfaces before and after removal from the vacuum chambers. Friction measurements are also a sensitive method of indicating contamination of nominally unlubricated metals. Diffusion-pumped systems employing improved backstreaming traps have recently been described where the wettability test has been cited as an indication of cleanliness (ref. 5).

A very common source of contamination in space simulation vacuum chambers arises from the use of plastic compositions for electric insulation. For example, many ball bearing tests are run with small electric motors that have

phenolic-type insulation. Evidence of the degassing was obtained in one instance, when, in a vacuum system (low pumping capacity), pressure increased about 3 decades (10^{-8} to 10^{-5} mm Hg. ranges) as a small motor was operated. Contaminants are apt to be nonpolymerized components or processing lubricants. Such contamination may provide lubrication to allow extended operation of bearings in the confinement of vacuum chambers but would soon be dissipated in the infinite vacuum of outer space. In many vacuum systems, pressure measurements are made at locations remote from the actual experiment and may not be indicative of equilibrium vapor pressure cells that can develop within an experimental configuration such as an electric-motor housing. Where several experiments are run simultaneously in a given chamber, the real pressure may be the vapor pressure of the most volatile component.

The temperatures that lubricated parts experience in scientific space experiments are believed to cover a small range such as -20° to 200° F. Passive (reflective parts, shields, etc.) temperature-control protection has been employed primarily for electronic equipment. When lubricated components must operate near power-generating equipment such as turbine drives or small reactors temperatures of 1000° F and higher can be realistic at the extreme low-pressure levels. A reentry vehicle may be required to have bearings in operation through extremes of pressures (760 to 10^{-10} mm Hg) and temperatures (-200° to 1700° F). In other similar devices, temperatures of 2000° F and higher may be anticipated.

A summary of the energy spectrum provided by space radiation is discussed in reference 2. That reference indicates that "space irradiation simulation should be possible by the use of a low energy (300 Kev and down)

electron beam in a high vacuum."

Simulation of radiation from nuclear reactors (such as those used for auxiliary power or propulsion systems) can only be provided in a research reactor. Dynamic lubrication experiments in gamma and neutron radiation can be useful as one step in the experimental procedure. Many investigators feel that radiation degradation of lubricating materials is a cumulative effect and that postradiation evaluation is satisfactory. Others consider that experiments must be run at anticipated flux levels, and that only dynamic lubrication experiments are significant. It would seem that, where possible, dynamic experiments are highly desirable in the full radiation spectrum and at the anticipated temperatures and pressures.

Dr. M. P. Hnilicka has indicated that experimental facilities for study of space problems should have a variety of capabilities as described in reference 6. These capabilities are associated with radiation, heat dissipation, vibration, acceleration forces, and space particulate matter. These comments were not particularly pointed to lubrication problems but should serve as a further guide in evaluating the variables that must be considered in the design of lubrication experiments for space applications.

LUBRICANTS AND LUBRICATING MATERIALS

Liquids

The use of common liquid lubricants in space applications must be limited because of vaporization of such fluids in the vacuum of outer space. Several experimental evaluations of vaporization have been made; for example, see figure 3. They show certain mineral oils, a diester, a polyphenyl ether, and

a silicone that have the lowest vaporization rates of available liquid organic lubricants. Experimental data, properly obtained, agree well with theoretical predicted data based on vapor pressure according to the Langmuir equation (ref. 5). General Electric Company's F-50 silicone is one fluid being considered for space equipment. Most fluids are mixtures of various compounds, contain volatile components, or are polymers with substantial ranges of molecular weights. In some cases manufacturers of liquid lubricants have made special efforts to eliminate the more volatile components. Attempts by users to remove volatile components from lubricants by distillation have resulted in marked changes in the properties of the lubricant because constituents important to the lubrication process have been removed.

Most measurements of vaporization rates for fluids have been made by using bulk fluid. These results may be misleading because the energy of adsorption of these fluids may have a marked influence on the evaporation of boundary lubricating films from solid surfaces. Since even one molecular layer may, in some cases, provide adequate lubrication, the importance of this interfacial energy on evaporation may be significant. A study in this area has been pursued at Frankford Arsenal, where monolayer desorption of special hydrocarbons after vacuum exposure is determined by friction measurements. Preliminary results suggest significant effects.

Design methods can be used to minimize vaporization of fluid lubricants. The most obvious approach is that of sealing the lubricated component in a housing with controlled atmosphere. Unfortunately, there are functional limitations in sealed systems such as excessive leakage or low seal life

and disadvantages such as increased weight and complexity. Because of present limitations of seal technology, a somewhat better approach is to restrict fluid losses by use of minimum clearance flow paths such as extended annular orifice. These can be very effective. For example, in the Tiros II Meteorological Satellite, ball bearings of an infrared radiometer (ref. 7) were run at 2750 rpm for several thousand hours without difficulty using the configuration of figure 4. An expression developed by Knudsen (ref. 8) and others makes it possible to calculate oil loss from the bearing based on molecular flow. This design has been described by M. B. Weinreb of NASA Goddard Space Flight Center (ref. 7). A more recent consideration of the system concept and various types of molecular flow seals is reported in reference 9.

A more commonly employed design method of restricting lubricant loss is the use of shielded bearings. It would seem that this also should be an effective method of restricting fluid loss. In shielded bearings and other devices, low energy surfaces (e.g., Teflon) can be utilized to prevent fluid loss through restrictions by surface wetting and subsequent creep.

The additive technology developed for improving lubrication depends on oxygen from the atmosphere. It has been demonstrated that typical materials which function by chemisorption will not lubricate in the absence of surface oxides (ref. 10). Also, with metals such as aluminum, some lubricants may function in vacuum, where direct reaction with nascent metals can occur, but not in air where protective and unreactive oxides are formed. In

conventional applications, the action of "extreme pressure" additives (including typical chlorine, sulfur, and phosphorous compounds) benefit by synergistic effects from oxygen. In some instances, the additive has been suggested to have the role of helping in the formation of oxide films. In conventional lubrication, oxygen is a vital but often ignored contributor to lubrication processes. Substantial quantities are usually dissolved and entrained in the lubricating fluid and also are present in the atmosphere and in metal oxide films. Experimental lubrication studies with additive systems in partial vacuum and inert gases may have produced misleading results because of dissolved or entrained air.

The experiences cited in literature show that the base fluid influences the effectiveness of an additive. Thus, an additive that functions well in a petroleum oil would not necessarily be effective in silicones. It has been suggested (ref. 11) that the dipole moment of the base oil contributes to effectiveness of "extreme pressure" additives in vacuum. The results to date are, however, too fragmentary to be considered conclusive.

Greases

Greases are very convenient to use as lubricants in small mechanisms. The limitations on the use of greases in vacuum are essentially the same for the base fluids. As suggested in reference 12, it could be expected that the gel structure would inhibit evaporation of the fluid. Figure 5 indicates that this may not be generally true. Since conventional greases lubricate by providing a continuous supply of the base fluid, the free fluid must be available at the surface. Therefore, the evaporation rate in vacuum should

be characteristic of the base fluid until the gel provides a portion of the exposed surface area. Data reported in references 12 and 13 show promise for grease-lubricated equipment in vacuum.

No comprehensive study of greases for space applications is known. No doubt compromises in grease requirements can be made that will allow the use of materials that have low vapor pressure. For example, high molecular weight waxes may find numerous uses, since they have low vapor pressures. Further, many of the lubrication problems are much less severe (i.e., loads and temperatures) than conventional applications, so that various low-vapor-pressure materials (such as silicones) can be used in spite of lubrication deficiencies..

Solid Compounds

Solid compounds including the inorganics (e.g., MoS_2 , and WS_2) and organic polymers (e.g., Teflon) are considered as lubricating materials in most problem areas where lubricated surfaces must be exposed to vacuum. Some compounds such as PbO are subject to dissociation (ref. 5), but most solid lubricants are useful in vacuum under much more severe conditions than organic liquids. Other compounds such as metal-free phthalocyanine that lubricate in air have been found to be inadequate for ball bearing lubrication in vacuum (unreported studies at National Research Corporation that were sponsored by NASA Goddard Space Flight Center). The dependence of graphite on continuing availability of adsorbates (such as moisture) for lubricating effectiveness is mentioned in most discussions of vacuum lubrications. It is certain that adsorbates contribute much to the lubricating

behavior of graphite. It is a mistake, however, to assume that graphite has no inherent lubricating ability in the absence of moisture. Rather, it can be useful in moisture-free systems at high temperatures (ref. 14) where metal oxide films are present. Recent work (ref. 15) on solid carbon-graphite bodies in vacuum suggests that such materials require further research to clarify the mechanism of lubrication with graphite.

The shear property of most solid lubricants such as MoS_2 are considered to be a function of planes of shear provided by crystal structure. Frequent reference has been made to the suggested role of adsorption of sulfur in lubrication by MoS_2 and WS_2 (ref. 16). Many research investigators discount the importance of that hypothesis and now feel that extraneous contamination was responsible for the effects noted. Vacuum studies of MoS_2 that employ mass spectrometers at Lewis Research Center have not obtained any evidence of elemental sulfur in the system.

Teflon and similar polymers have good stability in vacuum and can provide good lubrication. A primary limitation on the use of such materials in vacuum results from their poor heat-transfer capabilities. Local surface heating from friction causes decomposition of the polymers. Such decomposition has been verified by mass spectrometer data from room temperature friction studies at 10^{-9} mm Hg conducted by the Lewis Research Center. Decomposition of polymers may be by evaporation, molecular degradation or both.

Most solid lubricants are applied to surfaces as bonded films. Very often the bonding material limits the use of the film in vacuum service. Typical bonding materials include phenolic resins, silicone resins, epoxy

resins, sodium silicate, and various other inorganic compounds. The reservoir concept used early in the development of graphite-coated journal bearings has recently been utilized on retainer surfaces of rolling contact bearings (ref. 17). Burnished films and films deposited from volatile solvents or as pastes have been used in flight hardware. Dry-film-lubricated bearing surfaces have been shown to be susceptible to vibration in vacuum operation (ref. 18).

Metal Films

Metal films have long been considered as lubricants for use in vacuum (ref. 19). Barium, silver, gold, tin, and other metals are among the solid coatings shown (refs. 5, 19, and 20) to be useful as lubricants in vacuum. Coatings applied by vacuum vaporization, chemical plating, and electroplating methods have been used successfully as lubricants. Friction data on typical films are shown in figure 6. The shear process by which low friction is obtained with these coatings probably includes both solid shear and local viscous shear. Reference 19 suggests that a liquid film is formed; the poor heat dissipation in vacuum makes it is likely that local melting will often occur as a result of frictional heating. A study (ref. 21) showed that very thin gallium-rich liquid films on, and diffused into, bearing alloys can provide good lubrication in vacuum. Friction data with gallium lubrication are presented in figure 7. The methods and materials for use with gallium in vacuum lubrication need further study.

Lubricating Structural Materials

The use of materials with self-lubricating properties for parts of

mechanical devices is not new. In conventional practice, self-lubrication capability is a common basis for selection of many bearing and seal materials. When good lubrication cannot be assured, as in space devices, a self-lubrication capability for materials of sliding components can be of paramount importance.

Materials that have received most attention for space applications are those utilizing Teflon, MoS_2 , and similar compounds as the lubricating constituent. Typical metals used in such bodies are copper, silver, and nickel (refs. 22 and 23). Teflon bodies that employ fillers of glass fibers and MoS_2 have also been found useful (refs. 12 and 13). Mechanical carbons have not yet proved useful in vacuum, but, with further research, means may be found for utilizing their unique properties (ref. 15). Ceramic and cermet materials have been studied in vacuum to a very limited extent (ref. 24) with primary consideration given to high-temperature problem areas. Vehicle manufacturers, bearing manufacturers, and research organizations have active programs for high-temperature bearing materials to be used in vacuum.

Significant changes in the sliding behavior of nominally unlubricated metals can be achieved with inclusions of minor constituents in the structure of the metals (ref. 25). The inclusions are of sufficiently stable materials so they will not evaporate or dissociate in vacuum. During sliding, the inclusions replace the normal metal oxides as they are worn away. Effective inhibition of surface welding and good friction and wear properties can be obtained.

One commercially available bearing alloy, Stellite Star-J, is known to have the capability for maintaining a protective surface film. The behavior

of that alloy, as illustrated in figure 8, is attributed to the presence of SiO_2 formed in the casting process. Other minor constituents shown to inhibit surface welding in vacuum include FeS , NiO , and metallic tin (ref. 25).

FRICTION AND WEAR STUDIES

Friction and wear studies have been the most common basis for evaluating the material considerations described previously. These data are of fundamental and practical importance. In most instances the importance of the adhesion concepts of friction (ref. 10) have been demonstrated. Thus, fundamental adhesion investigations are of primary importance to practical friction and wear phenomena.

The type of experimental equipment used for adhesion, friction, and wear studies are shown in the self-explanatory sketches of figure 9(a) to (k). Many other devices could also be reported that are described in the references cited herein. All the devices designed for vacuum studies have common problems associated with vacuum systems. It is extremely difficult to have an apparatus in which the vacuum system has no influence on the experiment. Back-migration of diffusion-pump oils, ionization of particles in the chamber with ion pumps, and the capabilities of the systems to handle various gases are important considerations. Use of a mass spectrometer on a friction device equipped with ion-gettering pumps provides an interesting evaluation of pumping variables (fig. 10). Cryopumping with liquid helium provides the closest approach to the environment of outer space. The importance of pressure and type of vacuum pumping on friction is illustrated in figures 11 and 12. Mass surface welding was obtained at 10^{-7} mm Hg when

liquid helium was utilized for cryopumping to provide low partial pressure of oxygen.

A unique friction device shown in figure 13 was flown on two Ranger flights, which are reported in reference 26. Even in flight experiments, the possibility of contamination such as from an adjacent material may play an important role.

Many fundamental considerations have been projected into active and planned projects on friction, wear, and adhesion in vacuum. In most instances, the adhesion theory of friction has been utilized, but in specific problem areas, the Coulomb (roughness) effect and the electrostatic component of friction have also had careful consideration. The technical merit of selecting slider materials based on dissimilar metal combinations or solid solubility and alloying is usually recognized. Adhesion studies and some sliding friction studies have related the behavior of metals to a type of metallurgical structure. Maintenance of surface films is recognized as a primary device for preventing destructive surface welding. It has been shown that such films can be provided from the microstructural constituents of materials in sliding contact. Studies with single crystals have shown the importance of orientation and of planes of easy shear within the crystals of compounds and metals. It would seem reasonable that, in vacuum, an evaporative wear phenomena may occur that could be similar to corrosive wear in regard to the importance of thermodynamic factors. Utilization of the Peltier effect to influence heat dissipation from a friction surface has also been suggested. Nucleation and junction growth, surface elasticity, surface energy, crystal imperfections (dislocations), and so forth, can also

be added to the list of relevant factors. These factors represent a cross section of the considerations that enter into friction studies rather than a complete listing and are presented to emphasize the complexity of this area of study.

BEARINGS

Rolling-Element Bearings

Rolling-element bearings will find use in a variety of space applications. These include scientific experiments, communications equipment, guidance equipment, turbomachinery, boosters, and others. Rolling-element bearings will be required to operate under various speed conditions for various required lives. Types of service may be divided into three broad categories:

The first category covers the speed range from perhaps 100 to 12,000 rpm. Operation in this speed range may be intermittent or it may be continuous. Ambient temperatures will probably be moderate and not vary much above 200° F in most applications, but experimental work is being done at temperatures to 1500° F. Such temperatures may occur in bearings that operate close to hot turbines or reactors.

The second category includes speeds from a small fraction of rpm to about 100 rpm. It is expected that bearings in this group will operate at moderate temperatures. In the S-16 Satellite assembly designed by Ball Brothers Research Laboratories, the lower structure rotates at 30 rpm for stabilization purposes. The upper nonrotating structure, which houses the sensing instrumentation, is connected to the lower rotating structure through

a two-bearing shaft, so that the outer races of the bearing rotate. These bearings are 3308 size (40-mm bore) and R19 size ($1\frac{3}{16}$ -in. bore). While the bearing loads in orbit are negligible, the 3308 bearing must support the 13-g launch load exerted by the upper structure. The S-16 Satellite was required to operate for 6 months, which is the equivalent of 2 million revolutions, and has already functioned for more than twice that period.

Other applications exist for structural bearings of $1\frac{1}{2}$ - to $2\frac{1}{2}$ -inch bore diameters rotating at speeds of the order of 1/90 rpm.

The third category includes bearings for servo systems that find widespread use as positioning devices in scientific experiments. In each servo system, there are many gear-shaft support bearings that are required to operate intermittently in unidirectional or oscillating motion. Loads and speeds are nominal, but bearing torque is frequently very critical because of marginal power availability. Bearing breakaway torques must be low because of low starting torque in servo motors.

Bearings on which boosters are gimballed sustain high loads but for very short lives. In addition, they may not be required to operate in the hard vacuum of outer space, since most boosters perform their function before the ambient pressure reaches the level of a hard vacuum.

Fundamental problems. - The predominant problem with any type of bearing is the maintenance of a lubricant film on the contacting bearing parts that are in relative motion. Both evaporation of lubricants and denuding of normal contaminating (oxides) films are part of this problem.

Heat dissipation is a critical problem associated with the operation of rolling bearings in vacuum. In most bearing applications in ordinary

atmospheres, a copious quantity of the lubricant is circulated through the bearing. The heat generated in the bearing is partly transmitted to the lubricant, partly to the housing and shaft by conduction through the races from the rolling elements and retainer, partly to the surrounding atmosphere by convection, and partly to the surroundings by radiation. For a bearing exposed to a hard vacuum, two of the above four means of heat dissipation are not present. There is no atmosphere to which heat can be rejected by convection, and the use of copious quantities of recirculating lubricant is not feasible. A minimum quantity of oil, if any, will be present in the bearing, and this will serve only to lubricate rather than to lubricate and cool.

Therefore, it is apparent that heat will be rejected from the bearing by conduction to the housing and shaft and by radiation to the surroundings. Since heat transfer by radiation is a function of the difference of the temperatures raised to the 4th power, rejection of heat by this mode will not be significant unless the bearing temperature is high, or unless the bearing "sees" the absolute zero temperature of outer space. Any heat transferred to the shaft and housing by conduction will have to be rejected ultimately by radiation unless a throw-away heat sink is available.

Comparing the operation of a bearing in hard vacuum with that in an ordinary atmosphere shows the net result of this apparent difficulty in rejecting heat to be a higher bearing temperature and a greater temperature gradient between the points of sliding contact within the bearing and the exterior boundaries of the bearing. The difference in operating temperatures between a hard vacuum and an ordinary atmosphere is not expected to

be significant for operation at nominal speeds. At high speeds where heat generation rates become significant, however, this is a problem that could become serious. Careful attention must therefore be paid to the design of a bearing for a high-speed application in hard vacuum.

Rolling fatigue is a problem that must be coped with in ordinary application of rolling bearings where long life is expected. In any rolling-bearing application where the bearing is properly installed and lubricated, and not overloaded, failure will result from fatigue of the race or rolling-element material. Repeated stresses on an element of material eventually result in the formation of a microcrack. Further stressing causes the crack to propagate until a piece of material is broken away, resulting in a spall or pit. Fatigue life is sharply dependent on bearing load, varying inversely as the cube of the load. Since bearing loads in space vehicles will, in most cases, be negligible, fatigue is not expected to be a problem. An additional deterrent to fatigue may arise from the lack of a contaminating atmosphere in outer space. It has been postulated (ref. 27) that crack propagation is promoted by the presence of a contaminating atmosphere, because as soon as the crack surfaces are exposed to the atmosphere a contaminating film will be formed on them. This will prevent cold-welding of these surfaces and reclosing of the crack during the next stress cycle. In a hard vacuum, however, the freshly formed surfaces of the crack will remain clean and may cold-weld during the next stress cycle.

The final problem that may be critical in space applications of rolling contact bearings is wear. It has already been mentioned that surfaces can easily be stripped of contaminating films in a hard vacuum. Since the

presence of these films is frequently beneficial in reducing cold welding and galling by preventing the contact of clean surfaces, their absence might prove catastrophic. Severe welding, galling, metal transfer, and wear will probably follow the removal of the lubricant film, so that the importance of maintaining such a film is apparent. Metal transfer can destroy dimensional tolerances in rolling-contact bearings.

An additional factor that may promote wear is the complete lack of a bearing load. This may be a common occurrence in a zero-g environment. Severe skidding of the rolling elements on the races has been observed in high-speed, lightly loaded rolling-element bearings. Skidding results from a lack of traction due to insufficient load between the races. Severe wear accompanies skidding even in a normal atmosphere with adequate lubrication. In reference 28, the effect of roller slip on the wear of a 75-mm-bore roller bearing at 16,000 rpm was investigated. Reducing the load from 368 to 7 pounds resulted in an increase in wear rate of about 50 times. Retainer speeds varied from 98 percent of the no-slip speed at the 368-pound load to 5 percent at the 7-pound load.

Typical experimental studies. - The test assembly used at Marshall Space Flight Center in reference 18 is shown in figure 14. This device has been used for experiments with both 1/4-inch-bore ball bearings and 1/2-inch-diameter sleeve bearings. This rig is capable of operating at up to 8000 rpm with bearing torque measured. The test shaft is divided into two parts joined by a torsion spring, which is calibrated by determining the angular deflection under a known torque. The angular displacement of the spring is measured during test and converted into torque by measuring

the output from square wave generators consisting of two phototransistors. Bearing loads exerted in these experiments are nominal, of the order of a few grams.

The test rig used at Goddard Space Flight Center and reported in reference 20 (fig. 15) consists of seven small chambers each containing a small motor with test bearings and pumped with an 8-liter-per-second pump. The test chambers are arranged in a circular configuration with each chamber connected to a central chamber, which is pumped by a 40-liter-per-second vacuum pump. In this device, degassing of the motor insulation raises the test chamber pressure from 10^{-8} to 10^{-5} mm Hg. Again, the bearing load in these experiments is light, consisting only of the weight of the 5-watt-motor armature.

A successful bearing application in the Tiros II Meteorological Satellite (ref. 7) was previously mentioned. Eight ball bearings and five gears were included in a radiometer, which was driven by a low-power motor whose output torque is 0.03 inch ounces (fig. 4). The shaft speed for the bearings was 2750 rpm. The radiometer was operated satisfactorily for several thousand hours in orbit. Because of the marginal power available, low bearing torque was mandatory so that sealed bearings could not be used. Bearing housings with very close clearances around the shaft were designed to reduce the evaporation of lubricant from the bearings.

Bearing designs. - Minimizing heat generation in ball bearings means the use of open-race curvatures (e.g., race curvature is defined as the ratio of the ball groove radius to the ball diameter). Race curvatures of 54 to 58 percent rather than the standard curvatures of 51 to 52 percent should be

considered. Since the axial clearance in a ball bearing increases with increasing race curvatures, open-race curvatures cannot be used indiscriminantly. Greater than normal bearing radial clearances will be necessary in all medium- to high-speed applications because of the heat rejection problem. The temperature of the rolling elements will stabilize at a level that may be considerably above that of the races, because almost all of the heat generated in the bearing must be rejected by conduction through the races. This means that bearing operating clearance will be less than the initial clearance so that the latter must be liberal to allow the bearing to reach an equilibrium operating condition without complete loss of radial clearance. The use of bearing types with inherently high friction (for rolling-contact bearings) such as needle bearings should be avoided.

Retainer materials. - Where bearing operating temperatures do not exceed 275° F, nonmetallic retainers should be given serious consideration because of their light weight and inherent self-lubricating properties. Outer-race piloted retainers may offer some advantage in high-speed applications because of their self-balancing features. Some nonmetallic retainer materials, however, require a thin supporting shroud at high speed because of lack of mechanical strength. This precludes the use of an outer-race piloted retainer. Some nonmetallies exhibit excessive degassing in hard vacuum. This should be checked in the consideration of any material.

For temperatures from 275° to about 600° F, iron silicon bronze with or without silver plating is a satisfactory retainer material in conventional applications. At temperatures above 600° F, the strength of copper alloys deteriorates, and nickel alloys such as S-Monel become the best choice for

retainers. For space applications, lubricating coatings are often needed with such retainer materials.

Race and rolling element materials. - The choice of race and rolling element materials will be governed by the operative temperature range. For bearings whose maximum operating temperatures will not exceed 450° F, the conventional material SAE 52100 and 440 C steels should be adequate. At temperatures above 450° F, both 52100 and 440 C steels suffer a deterioration in hardness that makes them generally unsatisfactory as bearing materials because of reduced hardness and a greater susceptibility to brinelling. At higher temperatures, other alloys with greater high-temperature hardness merit consideration.

At temperatures above 1500° F, it will be necessary to use refractory metal alloys, cermets, and ceramic materials. Limited experience with cermets as bearing materials has shown that the titanium carbides are most suitable. Tungsten carbide is less suitable because of its extreme brittleness. Chromium carbide is sensitive to both thermal and physical shocks.

Ceramic materials are being considered for use in bearings at temperatures to about 3000° F. Among the ceramics being considered are aluminum oxide compacts, both hot- and cold-pressed molybdenum disilicide, tungsten disilicide, and zirconium oxide. Very little experience has been obtained with materials of this type in bearings, so that a real evaluation of them as bearing materials has yet to be made.

Sliding Bearings

Sliding bearings appear to be best suited for low-speed or oscillatory

applications. There are many hinges, latches, cams, and pawls contained within scientific experiments, communications equipment, and guidance equipment in which sliding bearings can be used efficiently. There appear to be a number of applications for pivot bearings for retractable arms, antennas and such. These will be called upon to operate only once, but the bearings may remain idle for a period of up to several months before being actuated. They offer the advantages of simplicity, less space requirements, and very high load capacity at low sliding velocities. They can also be made to operate at extreme temperatures with less difficulty than rolling-element bearings. They are suited for thrust vector gimbal bearings and certain airframe control bearings where the combination of high load, high temperature, and very low rotative speed exists.

The problems that exist in rolling bearings, namely, the retention of a lubricant film, prevention of surface damage in the absence of protective contaminant films, and heat dissipation, will also be present in sliding bearings. The prevention of surface damage in sliding bearings is not as critical as it is in rolling bearings, but the problem is aggravated by the difficulty of getting wear debris out of the bearing. Accumulated wear debris can accelerate the rate of wear. Heat dissipation may be more severe in sliding bearings than in rolling bearings because of the probability of higher rates of heat generation. As in rolling bearings, heat must be dissipated by radiation, either from the bearing itself or from the housing and shaft. Sliding bearings that will be subject to continuous service, whether oscillating or rotating, must be carefully designed to make certain that seizure does not occur before temperature equilibrium is reached.

The majority of experiments are conducted with simple specimens in sliding contact rather than with complete journal or thrust bearings. Sliding-friction tests with simple specimens, as described earlier, are used to screen materials and lubricants, because they can be conducted with less expenditure of time and money than can full-scale bearing tests. In most instances, tests with simple specimens are followed by bearing tests on the most promising material-lubricant combination.

Sleeve-bearing test programs have been designed to evaluate materials and dry-film-lubricant coatings at temperatures from -90° to 2000° F, with oscillating as well as rotating conditions, speeds to 15,000 rpm, and pressures down to 10^{-9} mm Hg. Dry-film coatings for plane bearings such as metal-free phthalocyanine, lead sulfide, and calcium fluoride, and materials such as mechanical carbons, aluminum oxide, silicon carbide, IT-1 metal ceramic, and several super alloys are being evaluated.

Estimates of operating temperature for both the journal and bushing can be made from heat-transfer considerations. Heat-generation calculations can be made based on load, speed, and friction coefficients obtained from basic friction tests, and the bearing can be designed with sufficient internal clearance to prevent seizure.

The accumulation of wear debris may be lessened by the use of axial grooves that allow the debris to exit from the bearing. However, care should be taken to provide liberal radii where the edges of the groove meet the bearing bore. Sharp corners must be avoided when using solid-lubricant bonded coatings because of the tendency of the corner to scrape the lubricant film off the surface moving relative to it.

Gas Bearings

Present day use of gas bearings in space applications is limited to gyro-gimbal bearings in ballistic missile control systems. This application requires a nearly frictionless support with negligible relative motion between the bearing parts. Externally pressurized gas bearings are ideally suited for applications of this type and also where extreme temperatures are encountered or where system contamination from liquid or solid lubricants cannot be tolerated. The extremely low friction characteristics of gas bearings makes them desirable for gyro-gimbal bearings because of the reduction in gyro drift rates and the consequent improvements in control system accuracy. In general, present day gas-bearing gyros do not employ closed-cycle systems and so are suitable only for short-life applications. A pressurized container of gas is carried along to supply the required gas. The quantity of gas required for a long-life application would make an open-cycle bearing system completely impractical.

Work on a closed-cycle system has progressed to the point where such a system appears feasible (ref. 29). The system described in reference 29 uses Freon vapor as the lubricant and employs thermal pumping from a solar- or nuclear-energy source.

Even with the establishment of the practicability of a closed-cycle gas-bearing system, the probability of gas bearings becoming widely used in space applications is low. The penalty for their use is added weight and complexity, which would not be acceptable unless the requirements for low friction cannot be met with any other type of bearing.

Self-acting or hydrodynamic gas bearings may find some use in sealed systems operated at high speeds and low loads. Such bearings do not require a circulating gas system, since they operate on the gas present in their environment. Their load capacity, however, is quite low and dependent on rotative speed.

Since gas bearings used in space applications will, of necessity, be operated in a gaseous environment rather than in the hard vacuum of space, the problems associated with operation in a hard vacuum (discussed above for rolling and sliding bearings) will not be present. However, the zero-g environment will aggravate the problem of whirl instabilities to which gas bearings are prone. The dynamic characteristics of both self-acting and externally pressurized gas bearings have been studied by a number of investigators. A few of the many reports published in this area are listed as references 30 to 34. While considerable progress has been made in developing gas-bearing technology, further work is necessary to gain a better understanding of their dynamic characteristics.

The need for a closed-cycle bearing supply system offers some disadvantages as regards weight and complexity. Further studies are required to determine the power requirements for thermal pumping and the characteristics of bearings lubricated with gases near the saturation point.

Magnetic Bearings

Bearing wear and surface damage can be completely eliminated if all material contact between shaft and bearing is avoided. The complete avoidance of all material contact without the presence of a viscous fluid

in the bearing gap would also result in low friction. This can be accomplished by floating the shaft in a magnetostatic field. The magnetic forces necessary to float the shaft can be obtained from either electromagnets or from permanent magnets. Permanent magnets are by far the more desirable because electromagnets require a continuous energy input. A magnetic bearing that utilizes permanent magnets is described in reference 35. An analysis was made of the expected load-displacement characteristics of the bearing and this agreed well with the experimental results.

A magnetic bearing that was developed for use in gyros is described in reference 36. This bearing utilizes electromagnets and so requires a steady input of energy. A tuned capacitor circuit is required to maintain stable equilibrium of the rotor.

Because of the many problems inherent in the operation of conventional bearings in the hard vacuum of outer space, magnetic bearings may eventually find widespread use in space applications. Their use would eliminate all of the problems associated with lubricants, wear, and surface deterioration, and torque limitations associated with marginal drive power.

At the present time, the chief disadvantage of magnetic bearings is their ratio of high weight to load capacity. This is especially true of a permanent magnet bearing. The low load capacity that presently characterizes magnetic bearings may not be disadvantageous if the mechanism does not have to be operative during launch. In this case, the only radial load sustained by the bearings is that due to unbalance of the rotating assembly.

Since very little effort has been expended to date on their development, significant improvements in load capacity and reductions in weight of magnetic

bearings can be expected in the future. Their many advantages, especially relative to space applications, make intensive development efforts on them appear to be worthwhile.

ELECTRIC CONTACTS

Static and sliding electric contacts are utilized in space devices for transmitting electrical energy in communications and power transmission. Experimental studies (refs. 23, 37, 38, and 39) have almost entirely been for guidance in the solution of problems in specific applications. In most instances, these studies have provided for testing apparatus components, and the usual configuration is a partly conforming brush contacting a cylindrical surface. Primary problems include contact noise, contact resistance, and contact useful life.

Typical current flow across sliding contacts for communications and power transmission is in the range of 10 to 1000 microamperes (ref. 23). The current densities do not approach those commonly used in systems operating in the earth's atmosphere. Therefore, it can be suggested that operation of sliding contacts (as with other friction surfaces) in a sealed chamber that has a controlled atmosphere is desirable (ref. 23).

Where electric contacts cannot be used in sealed systems, the problems are similar but more complex than those for other sliding surfaces in vacuum. Surface films that prevent surface adhesion and wear should be conductive, but many of the available lubricating materials such as MoS_2 are poor electrical conductors. Thus, heat generated by electrical resistance at the contact interface can accelerate degradation of the surface film. This

adverse condition is, in part, compensated by the very light surface load (e.g., 3.5 mg/circular mil of apparent contact area) and low surface speeds (1 ft/min) that is used (ref. 38).

Contact "radio noise" is a condition that is especially undesirable in communications circuits. Noise has been associated with friction and wear phenomena and contact resistance. Most sliding contact materials used successfully in space devices utilize combinations of noble metal alloys. Reference 13a, 37, 38, and 39 describe some of the background information and materials reported by Lockheed's Missile and Space Division.

Different organizations do not agree as to the advisability of using MoS_2 containing materials for sliding electric contacts. Objections to the use of MoS_2 are based on its poor conductivity. Others have indicated, however, that, when used in combination with conductive metals like silver, a composite film that has adequate conductivity is obtained. Another suggestion has been made that electron tunneling allows an extremely thin film of a nominally nonconductive material to have the needed conductivity. While the limitations on electron tunneling have not been explored in this case, it seems quite likely that prohibitively thick films of MoS_2 could easily form on a sliding interface.

A logical development for the area of sliding contacts should be that of conductive lubricating films to replace MoS_2 . A film of gallium (ref. 21) or, for that matter, the molten film that can be formed with metals like gold (as suggested in ref. 19) can have merit. The use of liquid-metal films would require careful and special selection of the contacting solids.

GEARS

Gearing is utilized in most space devices. With very limited power available in most scientific experiments, friction loss in gears can be critical. Neither surface welding nor excessive wear can be tolerated, and the fundamental problems in gears are the same as for other components that have solid surfaces in sliding or rolling contact. Sealed and conventionally lubricated gear units are advantageous but cannot always be utilized.

Typical gear studies for vacuum application utilize the "four square" principal (refs. 13a and 22a). Gears for space devices are made of conventional alloys, may carry significant surface stresses at high rotative speeds, and employ extreme reduction ratios. Solid-film lubricants and self-lubricating materials such as filled polymers have been used successfully. One interesting use of self-lubricating materials is in dummy or idler gears that form a lubricating transfer film on one of the load carrying gears (ref. 22a).

Heat rejection from gears is difficult as was previously discussed for rolling contact bearings. This factor and other related considerations suggest that mechanical design should be such that the gear tooth form will give minimum sliding.

Many devices have dynamic requirements that make it desirable to utilize very fine pitch gearing. Also, weight problems dictate the necessity for taking the maximum reduction ratio attainable in each pair of gears. In some units, total reduction ratios as high as 100,000:1 have been used. There have been instances when conventional design practice has been

disregarded, and beam failures occurred in preliminary operation with undercut tooth dedendum used in attempting to obtain extreme reduction ratios.

SEALS

The frequent mention of sealed units as a desirable approach to the lubrication problems of mechanical components emphasizes the importance of seals. Static seals can usually be obtained from either elastomers, plastics, or soft metals in a variety of designs that will perform well under a wide range of conditions. Dynamic seals present a difficult problem because perfect conformability of one moving solid surface with another is practically impossible. Since pressure flow through a leakage path is a function of pressure ratio, it is easy to understand that it would be difficult to seal from anything approaching atmospheric pressure (760 mm) to the extreme vacuum of outer space ($<10^{-13}$ mm Hg).

The experience of Tiros II (ref. 7) and some laboratory experiments where conductance was varied (ref. 9) illustrate the potential for molecular flow seals. Such seals can be effective when the high pressure is around 10^{-4} mm Hg. Design considerations can be developed from kinetic theory of gases (ref. 8). Molecular flow seals do not involve solid contact; rather they restrict leakage by employing small clearances and substantial leakage path distances and can incorporate other conductance restrictions to inhibit free molecular flow. Since the high pressure side of such a seal must be at a significant vacuum level, such as 10^{-4} mm Hg, which is determined by the vapor pressure of the lubricant, it is apparent that other seal types are needed for systems employing conventional lubrication.

Most sliding contact seals for vacuum systems utilize elastomers or plastics that cannot be used at significant surface speeds. No sliding contact seals are known that are useful at pressures lower than 10^{-6} mm Hg. Slider material considerations discussed previously are applicable to seals.

Dynamic seals that utilize liquid metals such as mercury or gallium as a buffer fluid to gain conformability have been considered for vacuum systems. While this approach has merit, no uniquely successful seals have been developed. Containment of the liquid metal is a significant sealing problem by itself in most designs.

The potential use of a seal must depend on the application. Substantial frictional energy can be dissipated in a sliding contact seal. Further, a no-leakage dynamic seal is virtually unobtainable for such extreme pressure ratios. Seal assemblies can provide an effective restriction to leakage into vacuum, and, in many instances, tolerable leakage rates may be obtainable for flight packages.

CONCLUDING REMARKS

1. Critical lubrication problems have been associated with the operation of mechanical components in vacuum. Such components include rolling-element bearings, sliding bearings, sliding electric contacts, gears, and dynamic seals. Studies have been in progress toward the solution of these problems within the limiting conditions of specific designs.

2. The primary factors causing lubrication problems in space environment are the low pressure (e.g., 10^{-13} mm Hg) and the lack of oxygen. Such extreme vacuum conditions cause rapid evaporation of conventional lubricants and

complicate the problem of dissipating frictional heat. When lubricant films are evaporated from or displaced from a lubricated surface, normal surface oxides of metals prevent failure. If the oxides are dissociated or worn from the surface, they cannot re-form in extreme vacuum. The resultant denuded metals will readily form interfacial welds that can provide either complete seizure or local metal transfer. Transferred metal is apt to destroy necessary operating tolerances in mechanical components.

3. A systems concept that uses dynamic seals has been used successfully to provide lubrication. Where the maximum pressure is the vapor pressure of an available organic fluid, a molecular flow seal can provide significant reduction in lubricant evaporation rate. Bearings can be lubricated by lubricant vapor when operating conditions are not severe; the limitations have not been established. Successful flight operation has been obtained with a variety of mechanical devices.

4. Improved materials have been sought for use in lubrication problems where direct exposure to space environment cannot be avoided. Solid inorganic compounds (MoS_2), high molecular weight polymers (Teflon), and bearing alloys with film-forming microconstituents (Stellite Star-J) are examples of materials that have been found useful. These approaches are being expanded by many organizations, and significant attention is being given to ceramic-type materials. The value of such studies will become more significant as space devices are required to operate at more severe mechanical and thermal conditions as well as in nuclear devices.

5. Fundamental understanding is being advanced in adhesion and friction and wear studies. A multiplicity of factors have been suggested as important.

Rigorous investigations are required in this area to assess physical, chemical, metallurgical, and other factors properly.

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FIGURE TITLES

1. CS-22181 Pressure as a function of altitude.
2. Effect of pressure on incidence of molecular contact at 20° C.
3. Vacuum evaporation of various liquid lubricants for ambient pressures from 10^{-6} to 10^{-7} mm Hg.
4. CS 23439 Tiros II radiometer spindle assembly.
5. CS-22242 Evaporation rates for various oils and greases in vacuum from 8.0×10^{-7} to 2.0×10^{-6} mm Hg.
6. CS-22252 Friction and wear of alloys with various coatings in vacuum from 8.0×10^{-7} to 2.0×10^{-6} mm Hg. Sliding velocity, 390 ft/min; load, 1000 g; duration of run, 1 hr.
7. CS-25244 Coefficient of friction for Al_2O_3 sliding on pretreated gallium coated 44C-C at 10^{-9} mm Hg. Load, 1000 g; duration of run, 1 hr; temperature, 75° F.
8. CS-22261 Photomicrographs and surface profile tracings of wear areas on disk specimens. Load, 1000 g; sliding velocity, 390 ft/min; duration of run, 1 hr $\times$ 20.
9. Friction, wear, and adhesion apparatus.
 - (a) (7250-S) Adhesion - General Dynamics - Convair.
 - (b) (7251-S) Adhesion - Syracuse University.
 - (c) (7252-S) Adhesion - Rensselaer Polytechnic Institute.
 - (d) (7249-S) Cohesion - National Research Corporation.
 - (e) (7259-S) Friction - Armour Research Foundation.
 - (f) (7256-S) Friction - Atomics International.

- (g) (7257-S) Friction - General Electric - General Engineering Laboratories.
 - (h) (7253-S) Friction - General Electric - Research Laboratories.
 - (i) (7254-S) Friction - General Dynamics - Convair.
 - (j) (7260-S) Friction - National Research Corporation.
 - (k) (7265-L) Friction - NASA Lewis Research Center.
- 10. CS-24229 Ion-pumped vacuum system (mass spectrometer data).
 - 11. CS-22249 Coefficient of friction for 52100 sliding on 52100 at various ambient pressures. Sliding velocity; 390 ft/min; load, 1000 g; temperature, 75° F.
 - 12. CS-22248 Coefficient of friction for 52100 sliding on 52100 in vacuum with liquid helium pumping.
 - 13. CS-23438 JPL Ranger friction experiment.
 - 14. 7261-S NASA Marshall Space Flight Center bearing apparatus.
 - 15. 7263-S NASA Goddard Space Flight Center bearing apparatus.

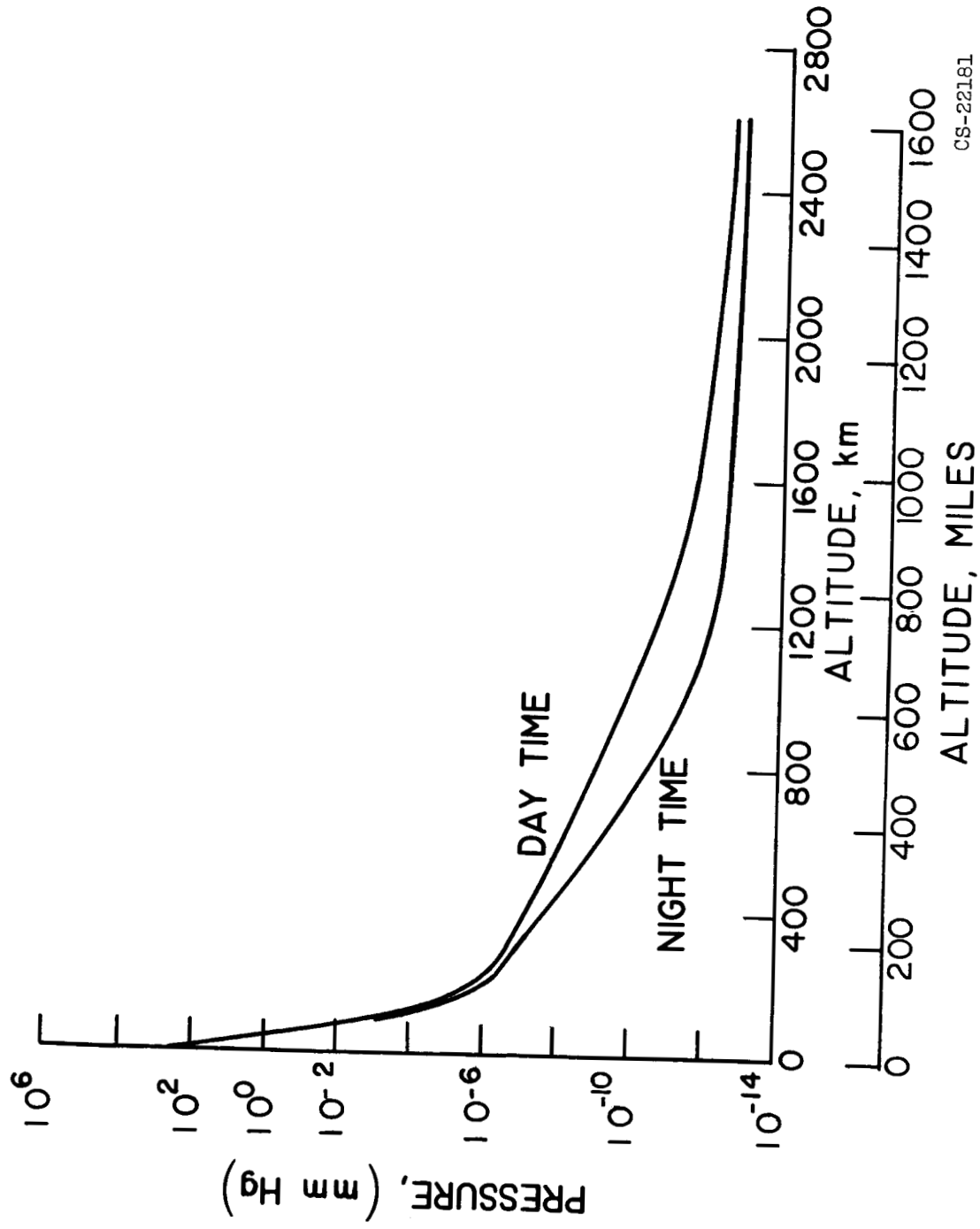


Figure 1. - Pressure as a function of altitude.

CS-22181

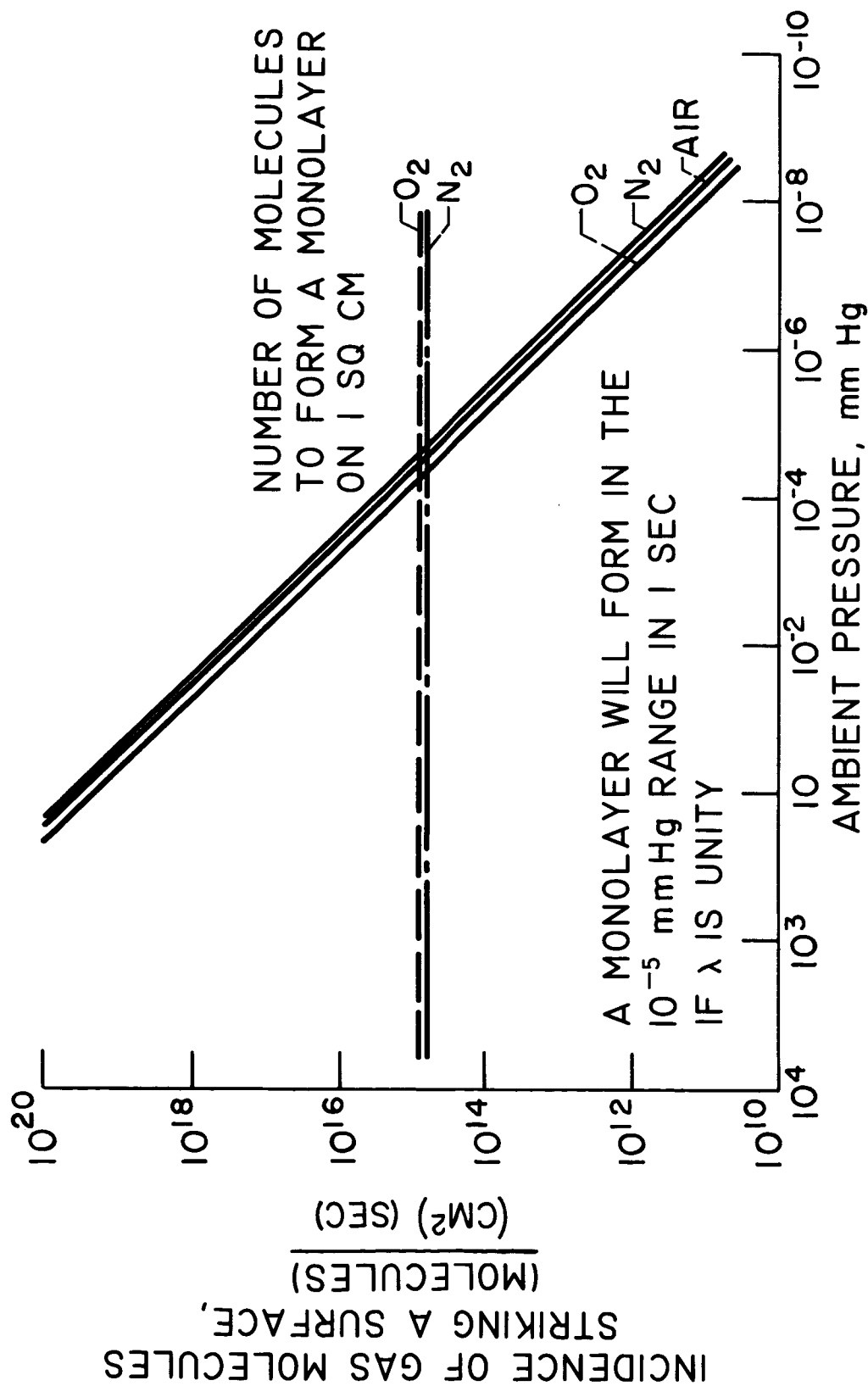


Figure 2. - Effect of pressure on incidence of molecular contact at 20° C.

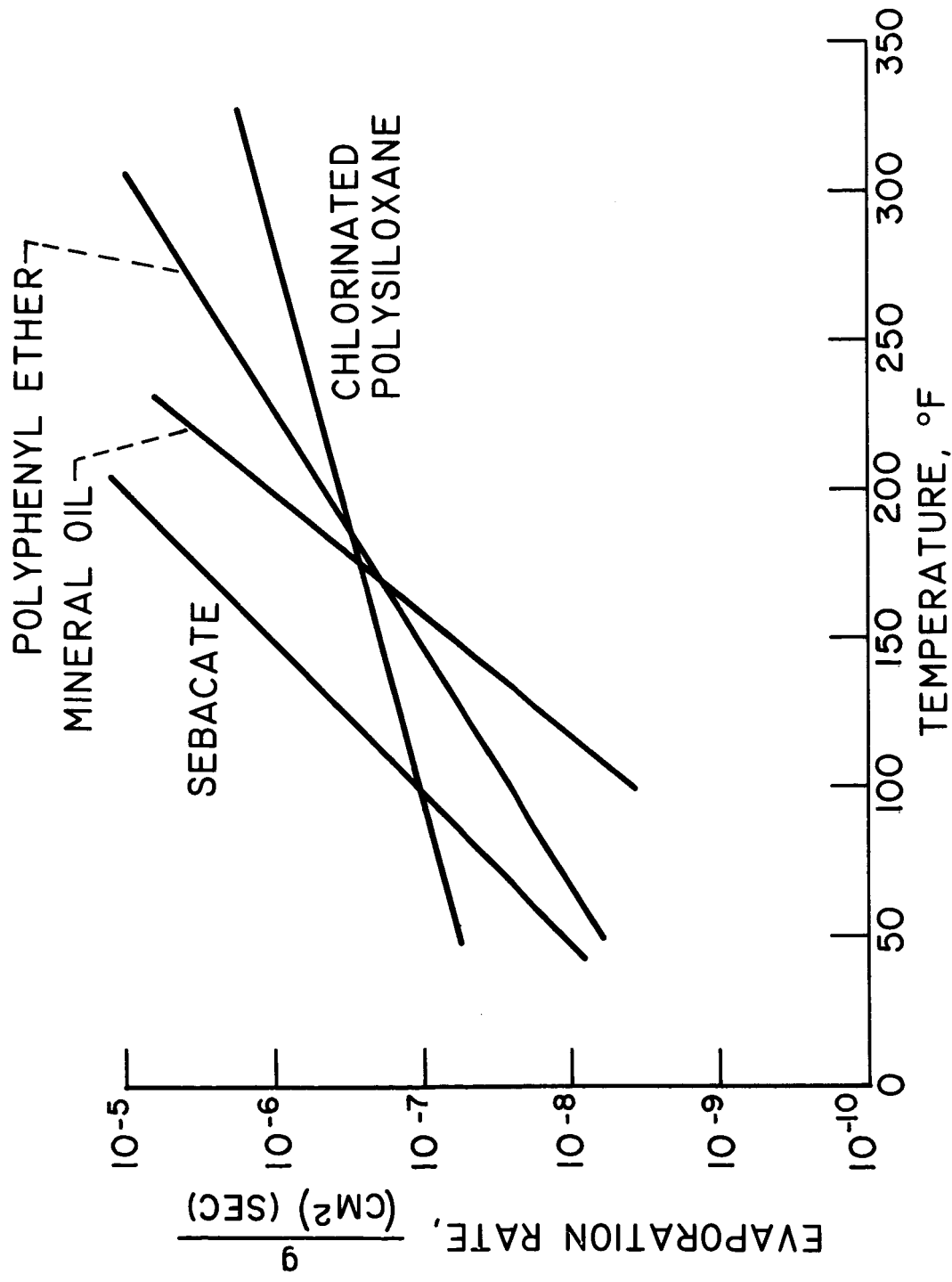
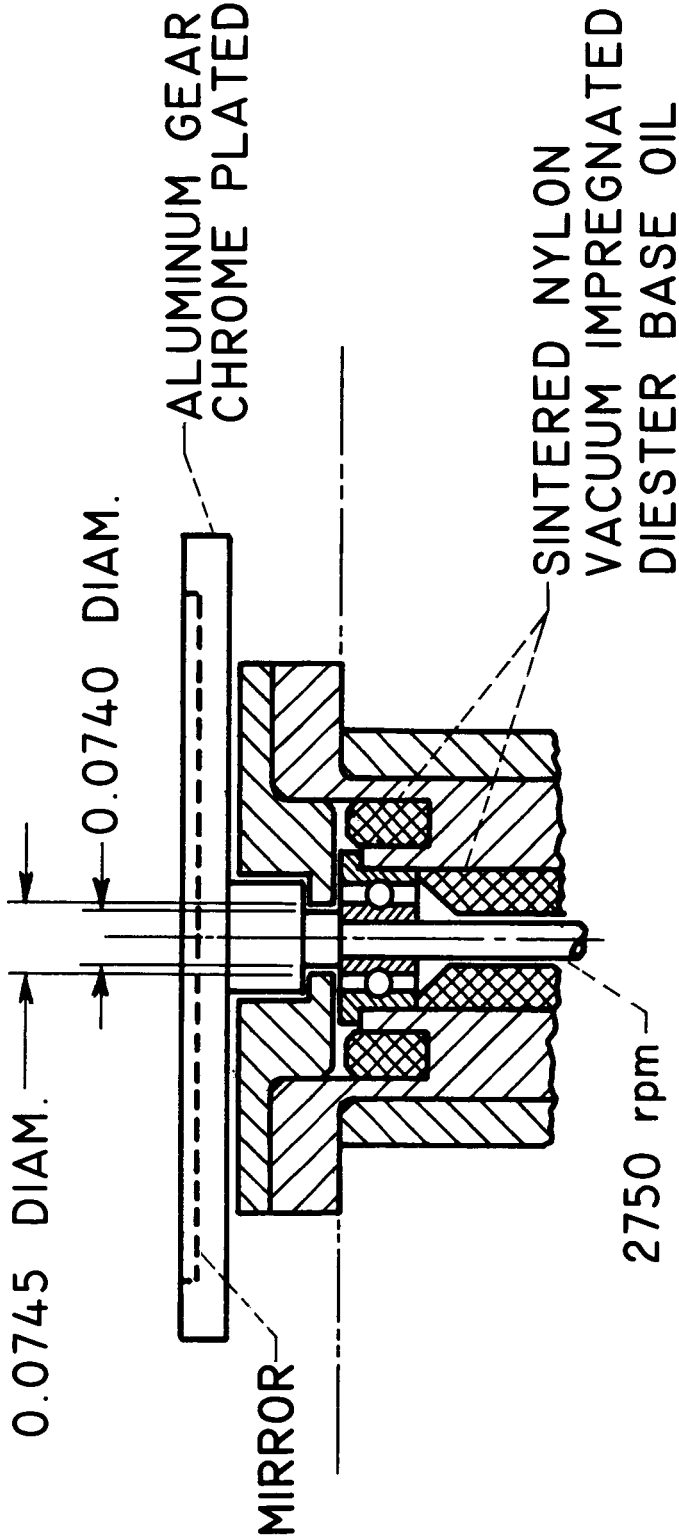


Figure 3. - Vacuum evaporation of various liquid lubricants for ambient pressures from 10^{-6} to 10^{-7} mm Hg.



CS-23436

Figure 4. - Tiros II radiometer spindle assembly.

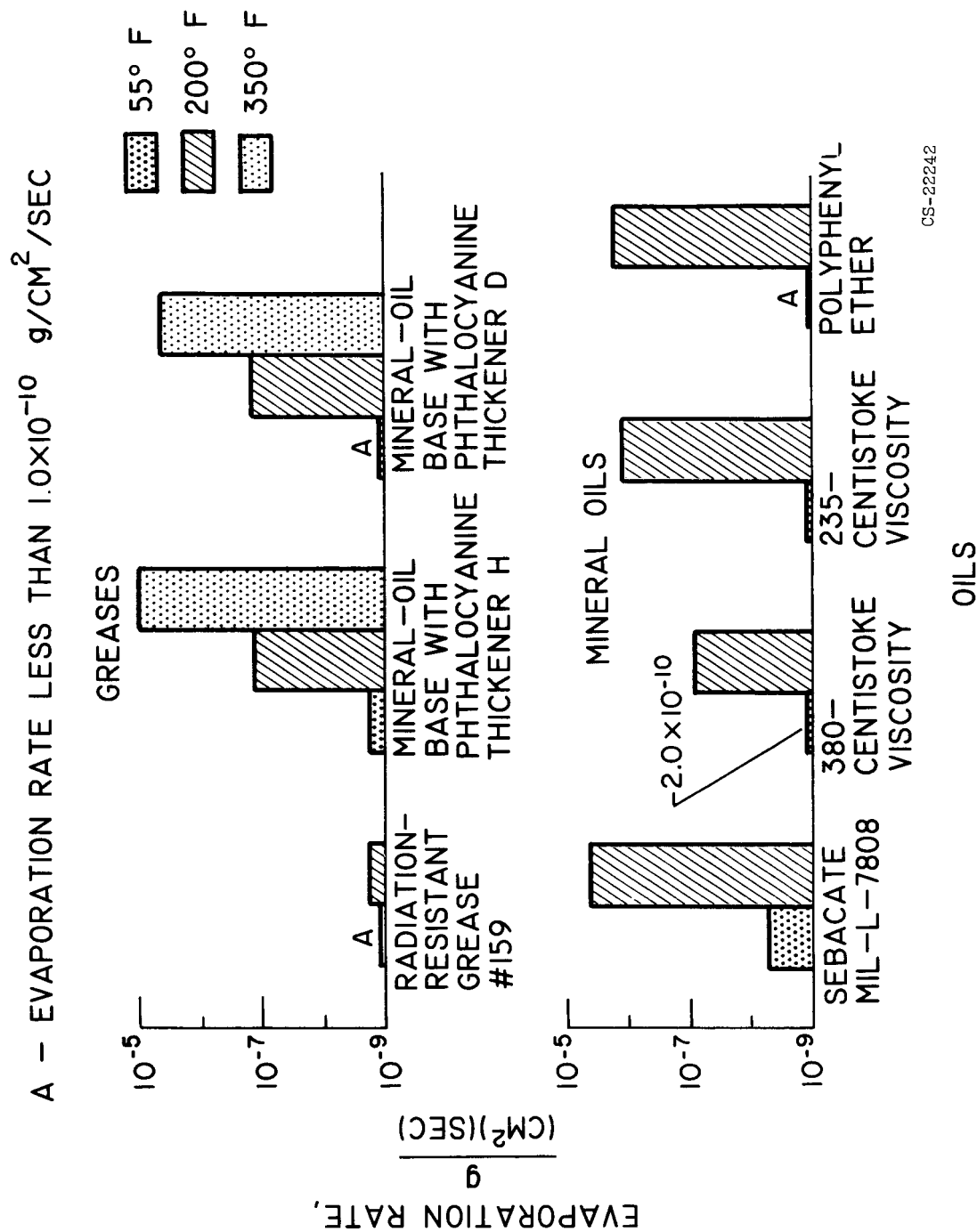


Figure 5. - Evaporation rates for various oils and greases in vacuum from 8.0×10^{-7} to 2.0×10^{-6} mm Hg.

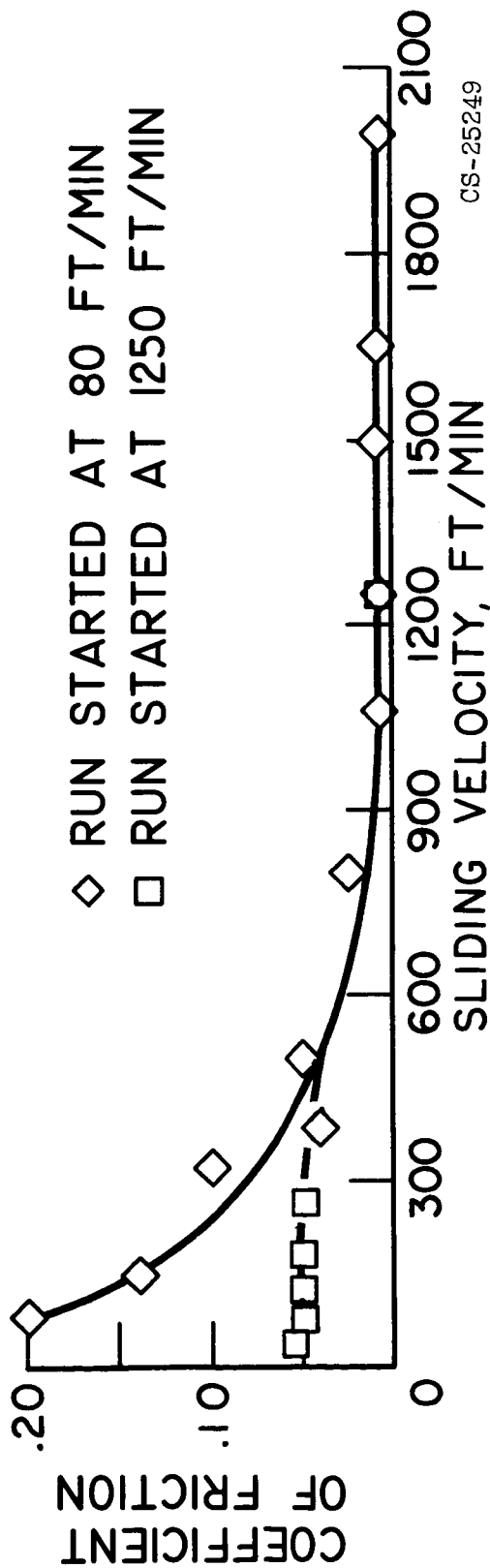


Figure 7. - Coefficient of friction for Al_2O_3 sliding on pretreated gallium coated 440-C at 10^{-9} mm Hg. Load, 1000 g; duration of run, 1 hr; temperature, 75°F .

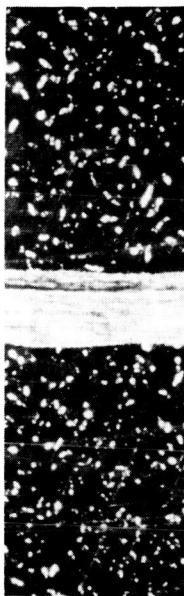


DISK SPECIMEN,
Ni-Cr ALLOY IN AIR

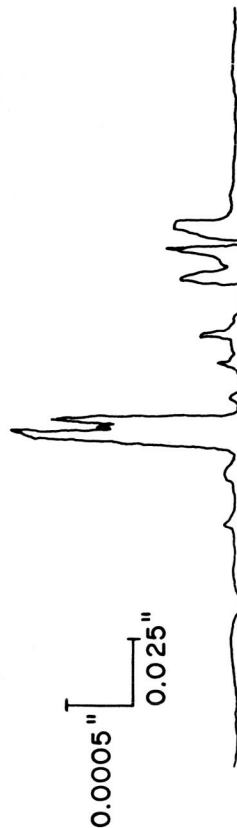


DISK SPECIMEN,
COBALT-BASE ALLOY IN AIR

0.0005"  0.025"



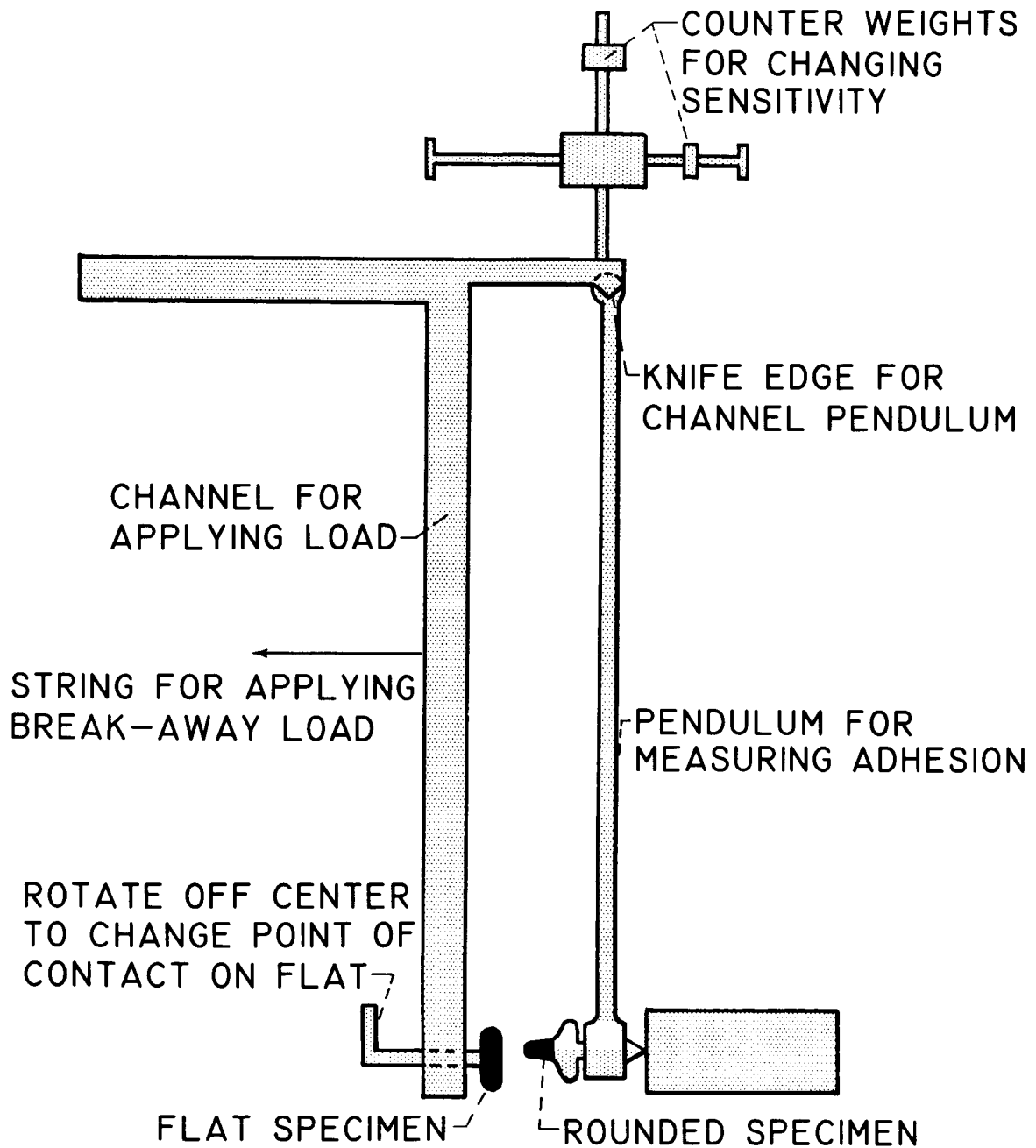
DISK SPECIMEN,
COBALT-BASE ALLOY IN VACUUM



DISK SPECIMEN,
Ni-Cr ALLOY IN VACUUM

CS-22261

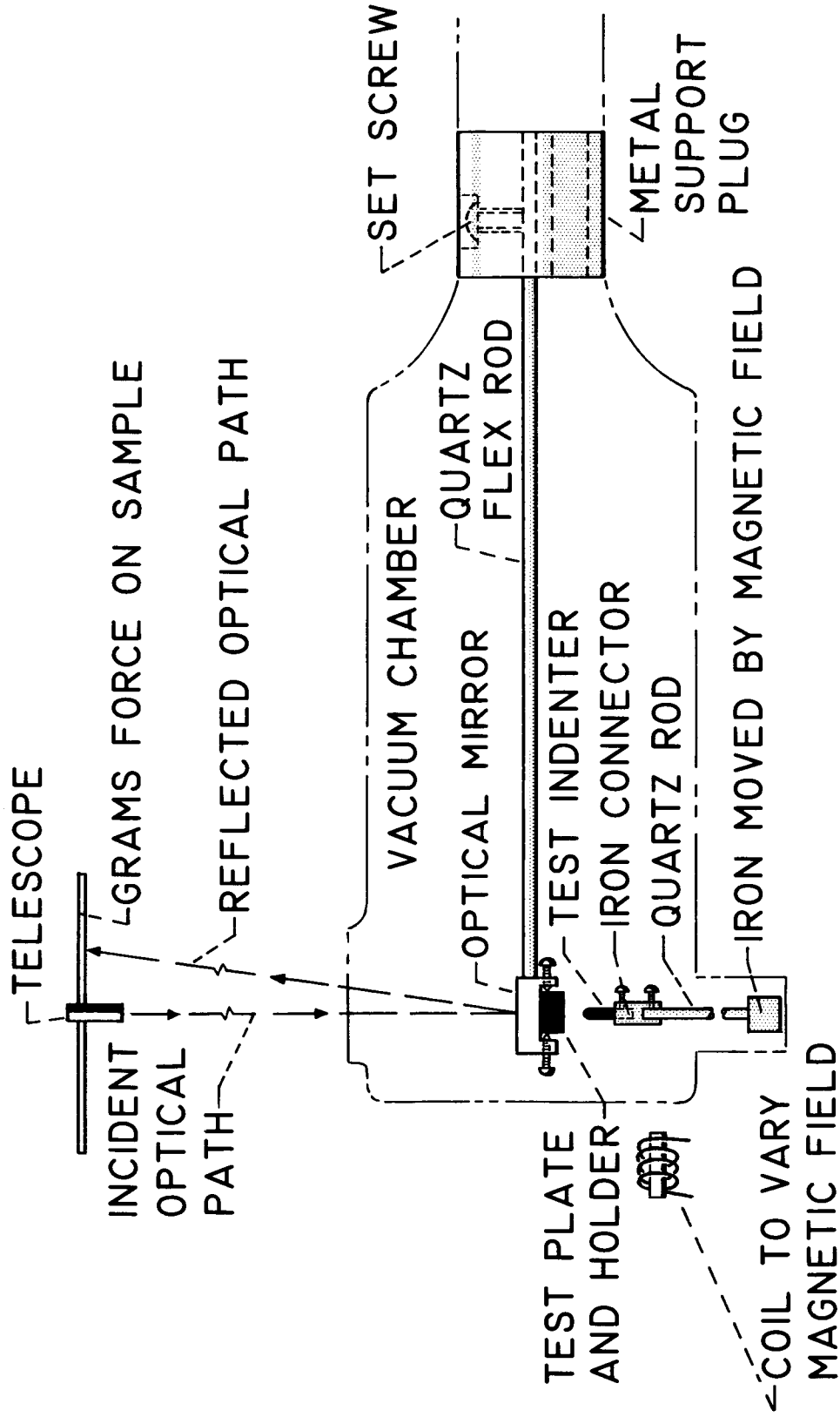
Figure 8. - Photomicrographs and surface profile tracings of wear areas on disk specimens. Load, 1000 g; sliding velocity, 390 ft/min; duration of run, 1 hr. X20.



/CD-7250/

(a) Adhesion - General Dynamics - Convair.

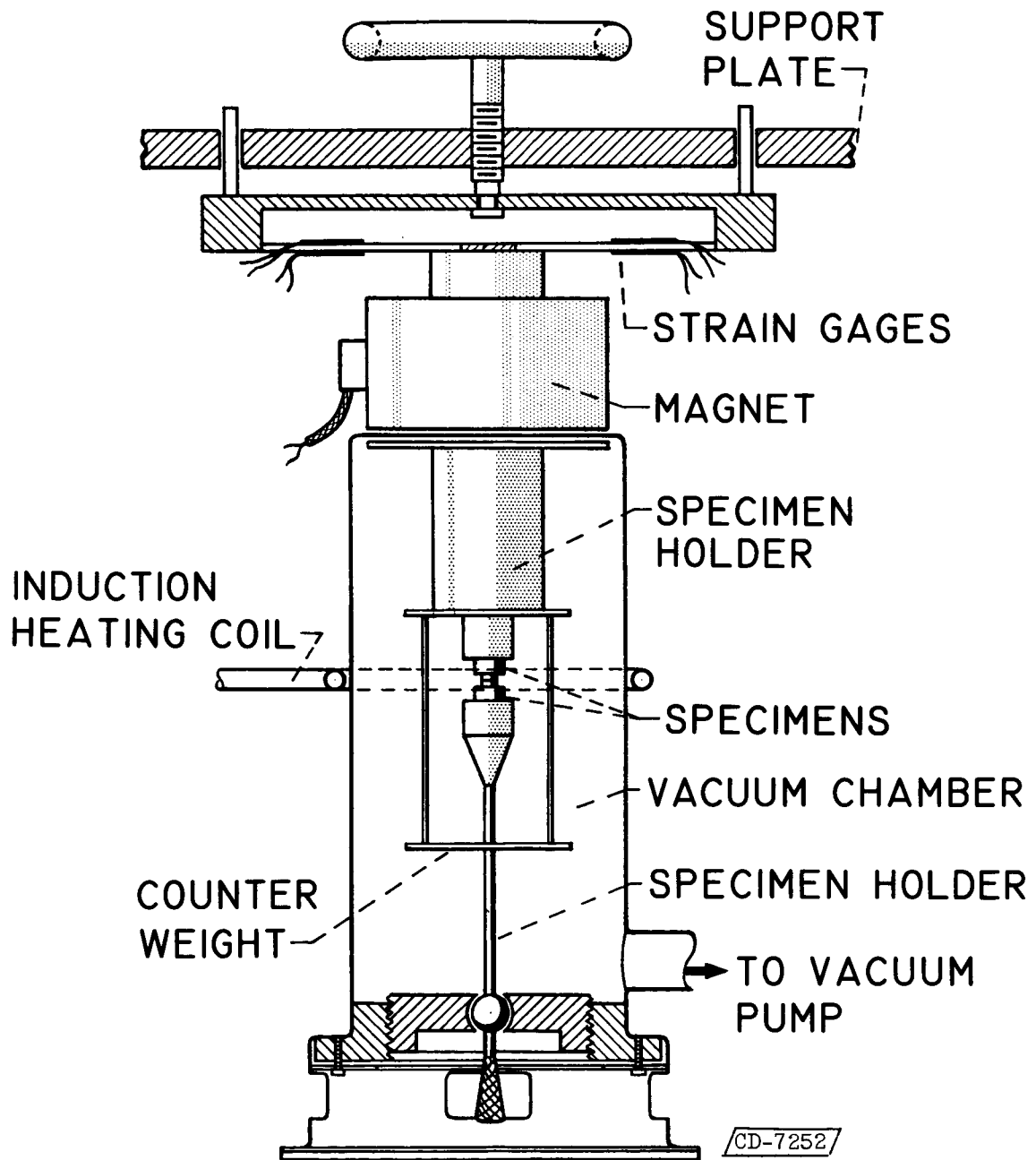
Figure 9. - Friction wear and adhesion apparatus.



CD-7251

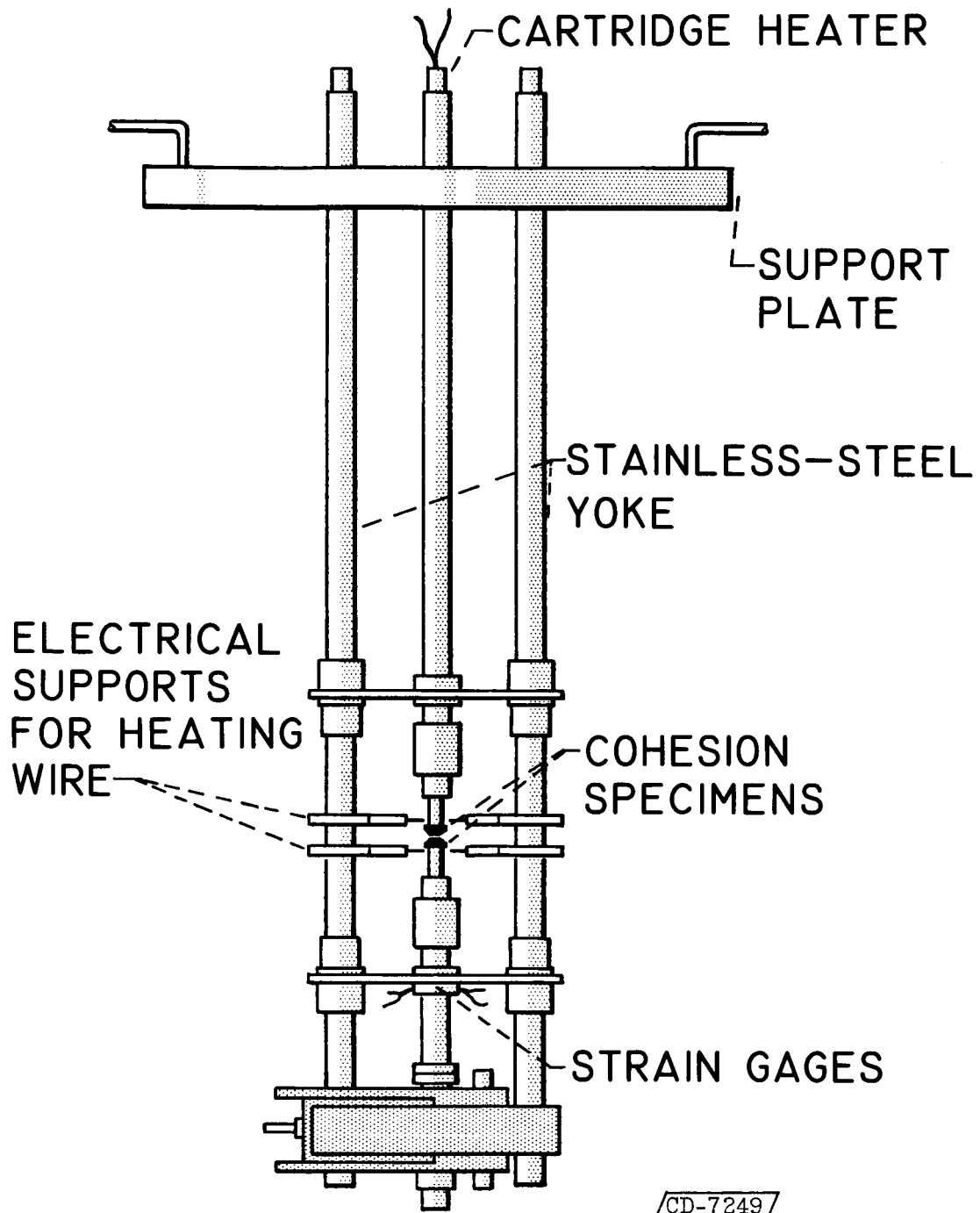
(b) Adhesion - Syracuse University.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



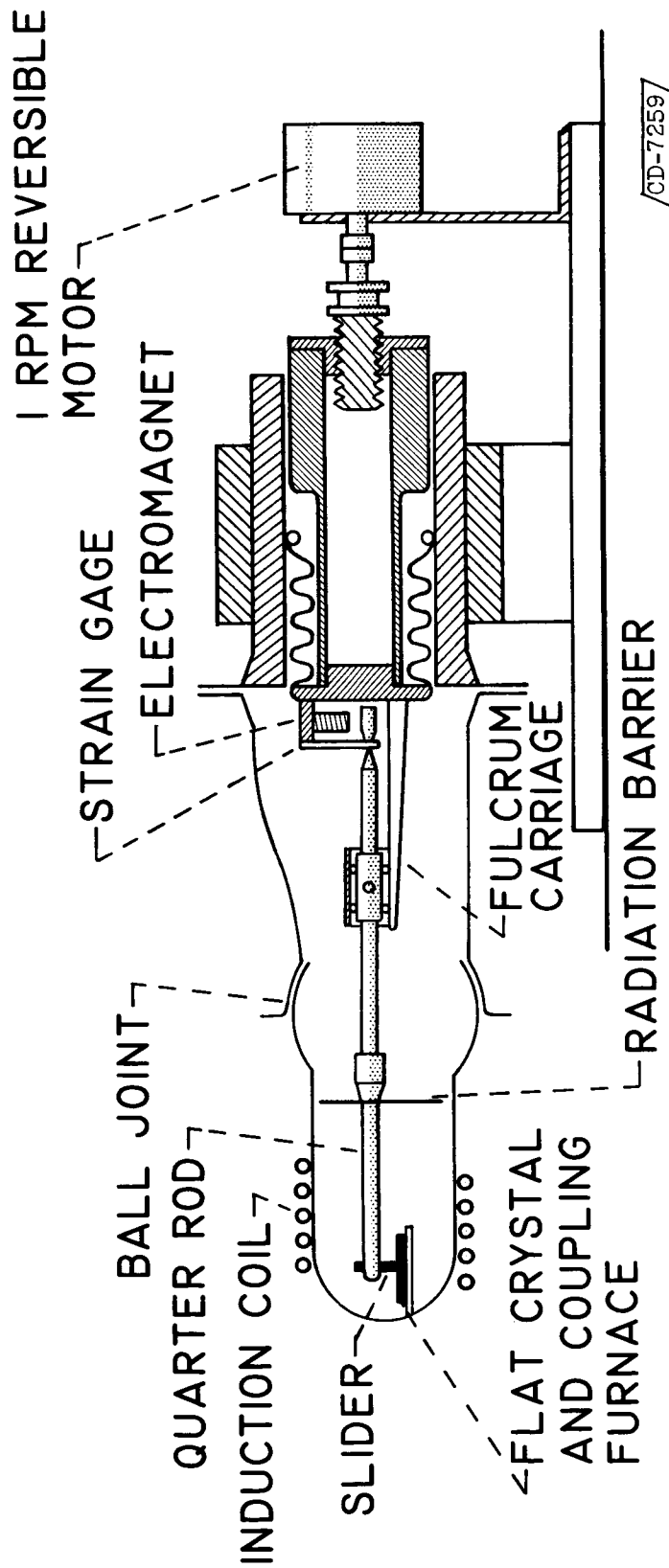
(c) Adhesion - Rensselaer Polytechnic Institute.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



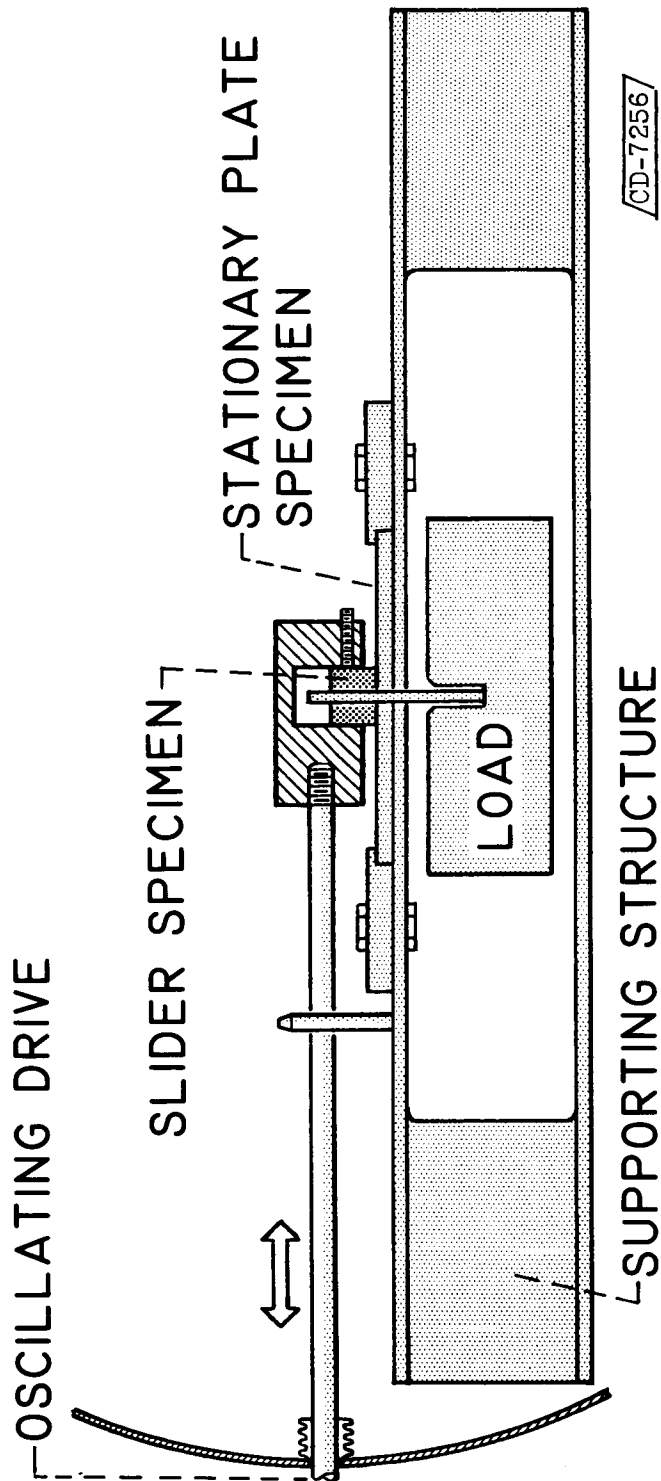
(d) Cohesion - National Research Corporation.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



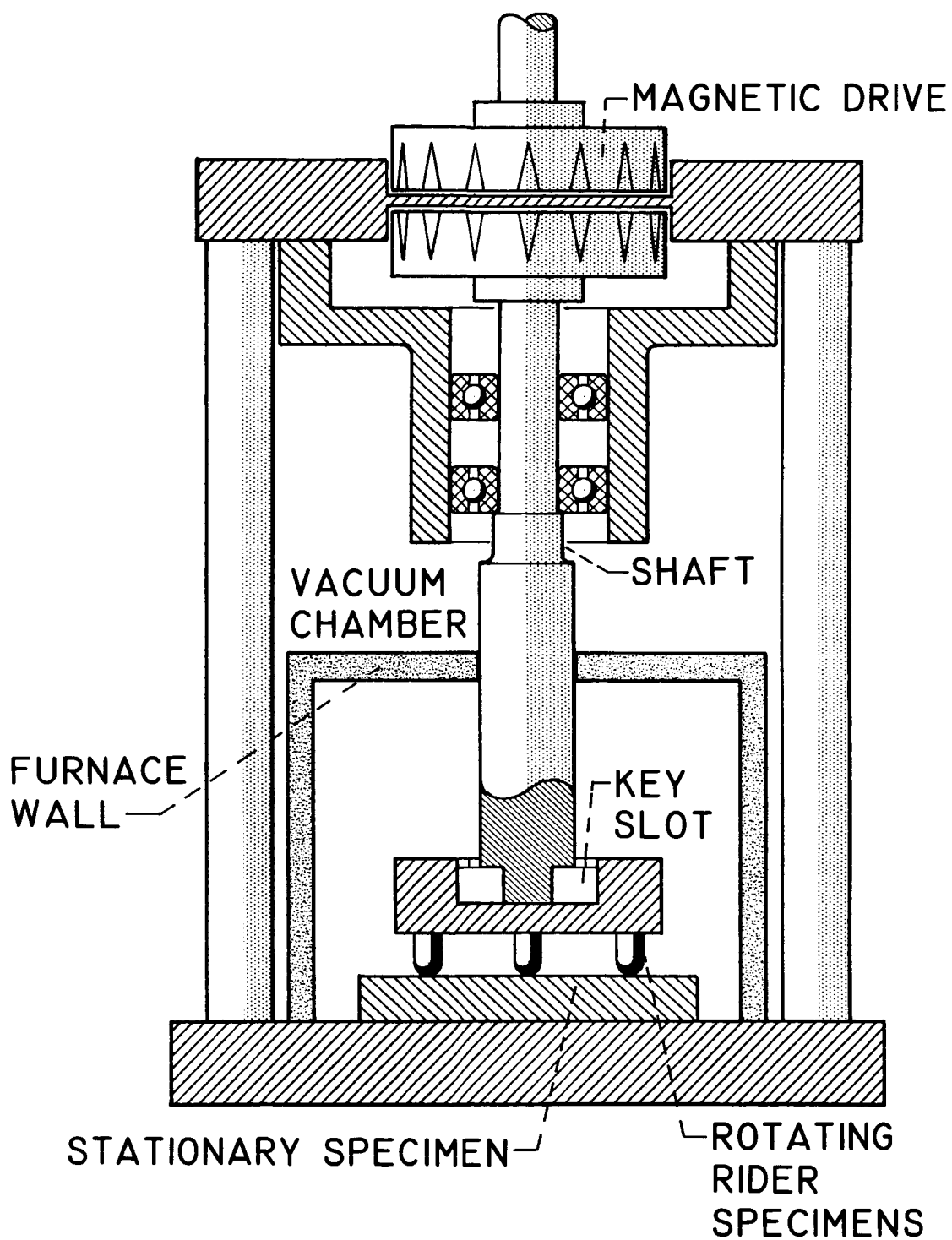
(e) Friction - Armour Research Foundation.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



(f) Friction - Atomics International.

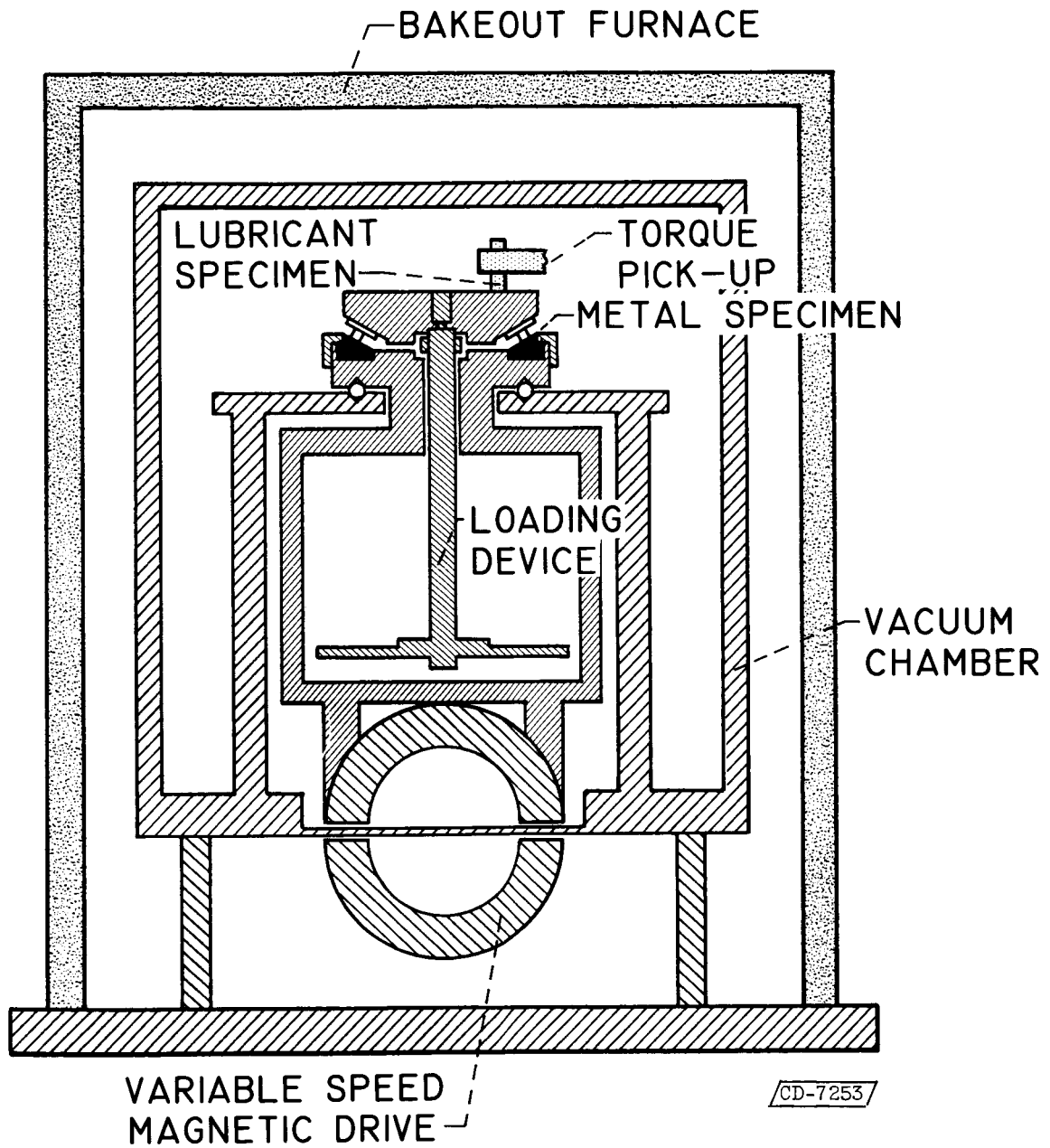
Figure 9. - Continued. Friction, wear, and adhesion apparatus.



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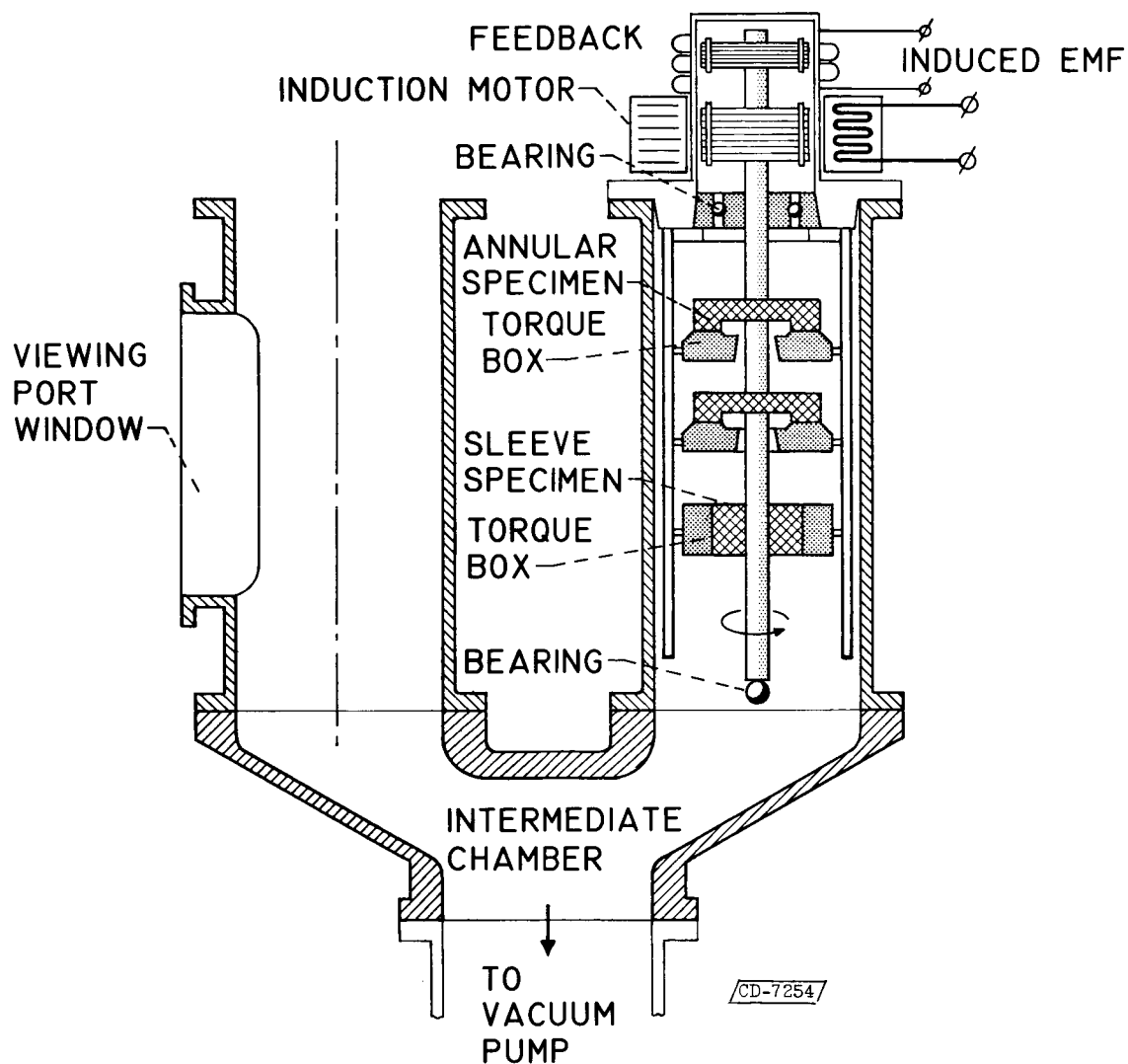
(g) Friction - General Electric - General Engineering Laboratories.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



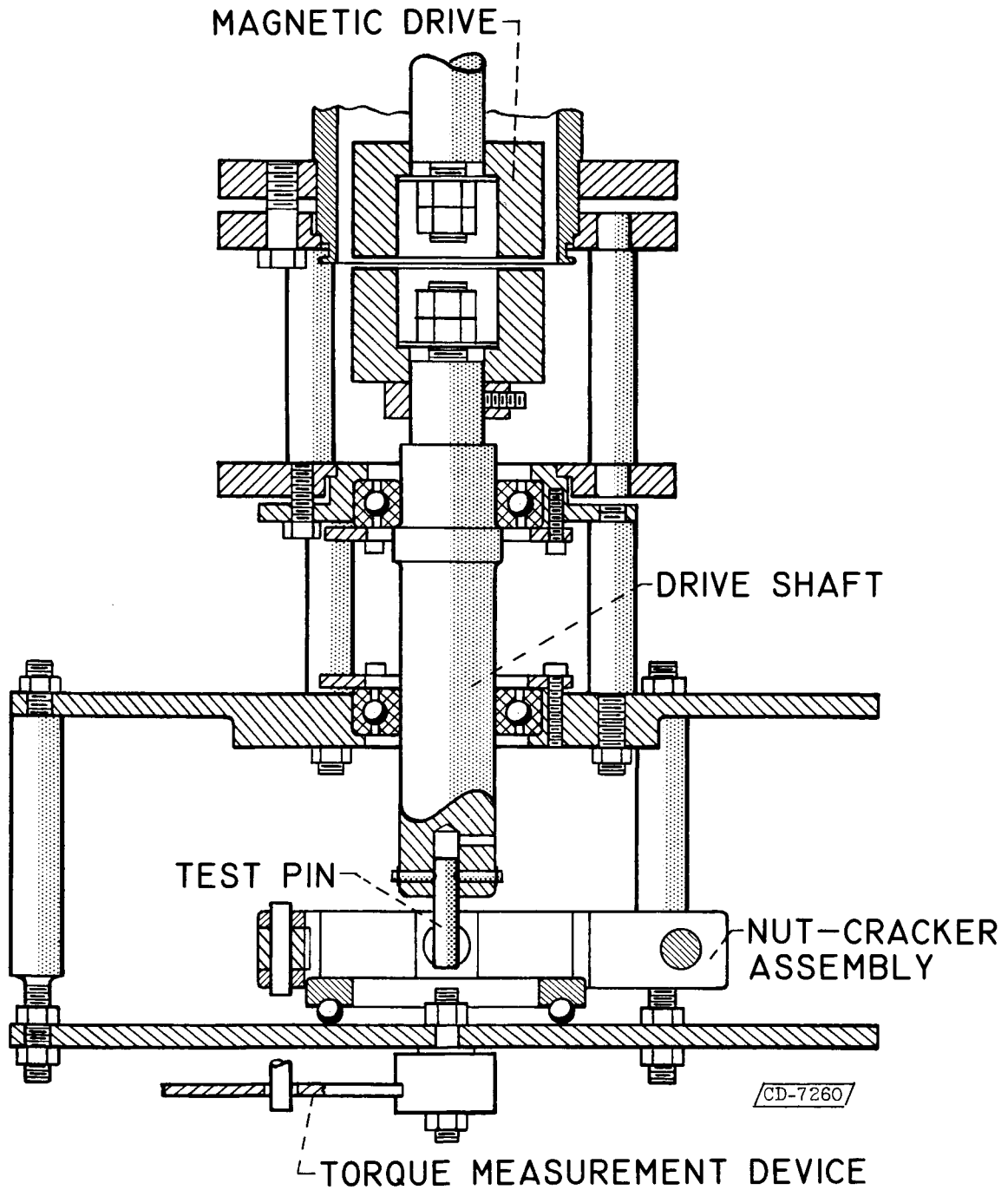
(h) Friction - General Electric - Research Laboratories.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



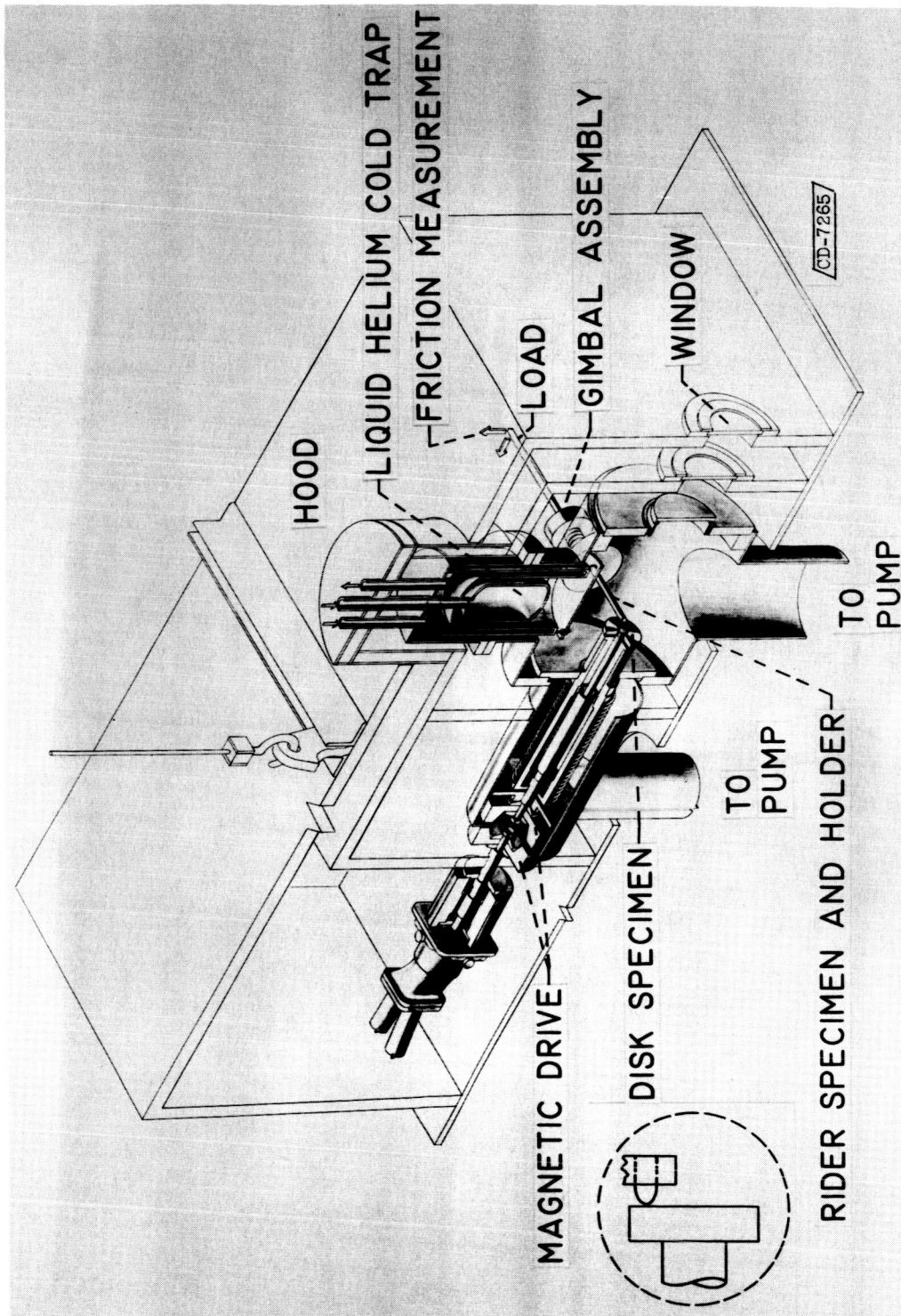
(i) Friction - General Dynamics - Convair.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.

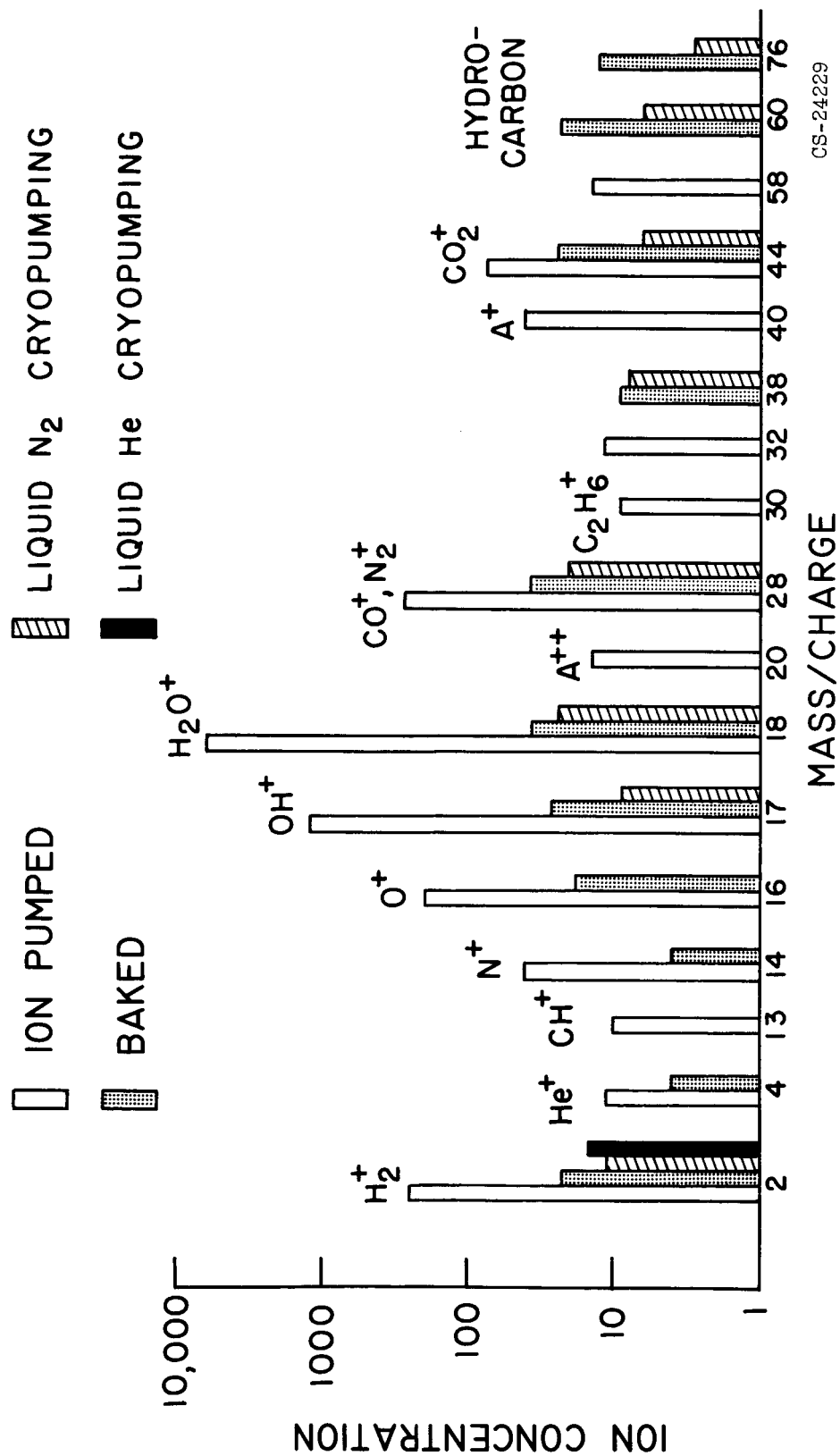


(j) Friction - National Research Corporation.

Figure 9. - Continued. Friction, wear, and adhesion apparatus.



(k) Friction - NASA Lewis Research Center.
 Figure 9. - Concluded. Friction, wear, and adhesion apparatus.



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Figure 10. - Ion-pumped vacuum system (mass spectrometer data).

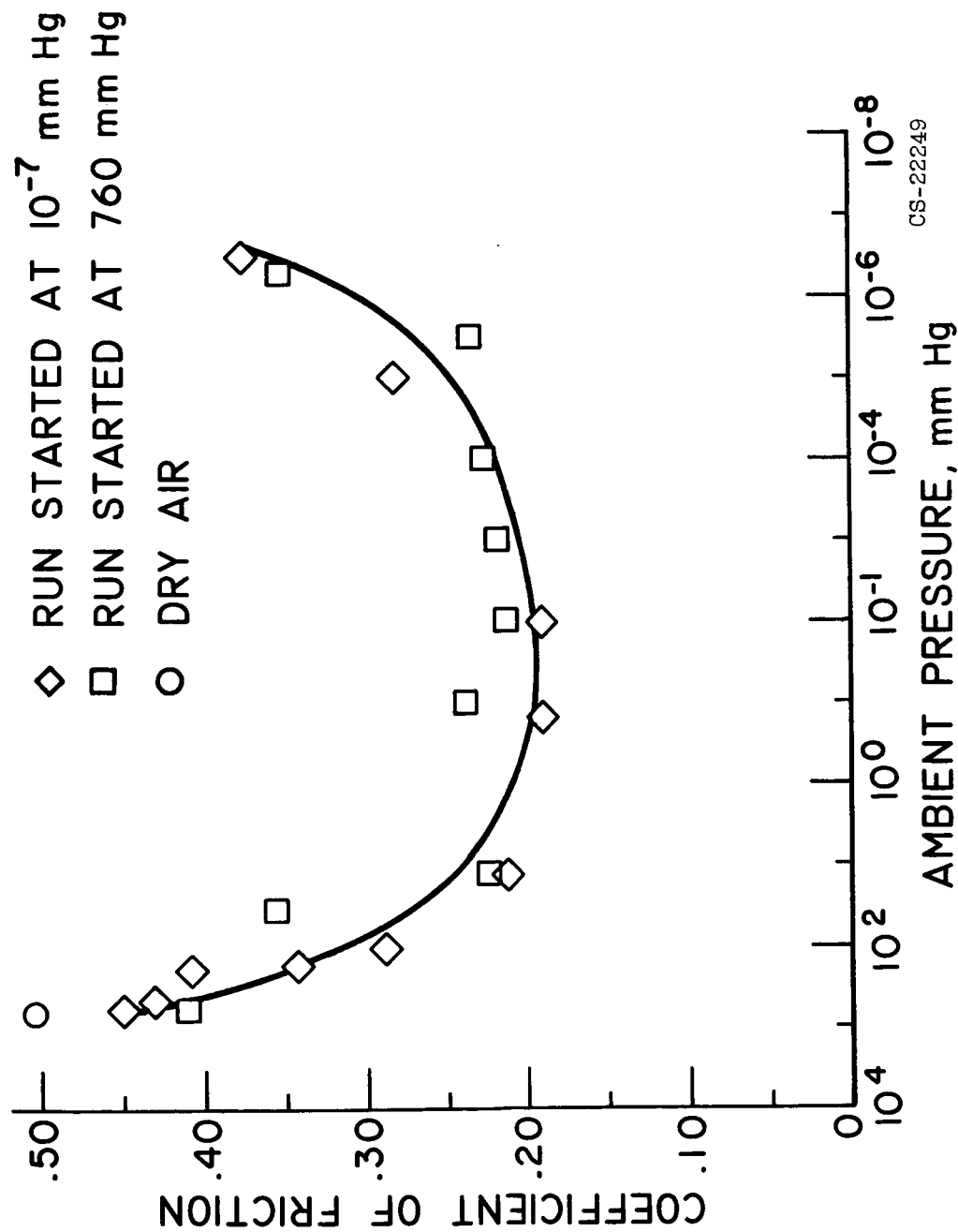


Figure 11. - Coefficient of friction for 52100 sliding on 52100 at various ambient pressures. Sliding velocity, 390 ft/min; load, 1000 g; temperature, 75° F.

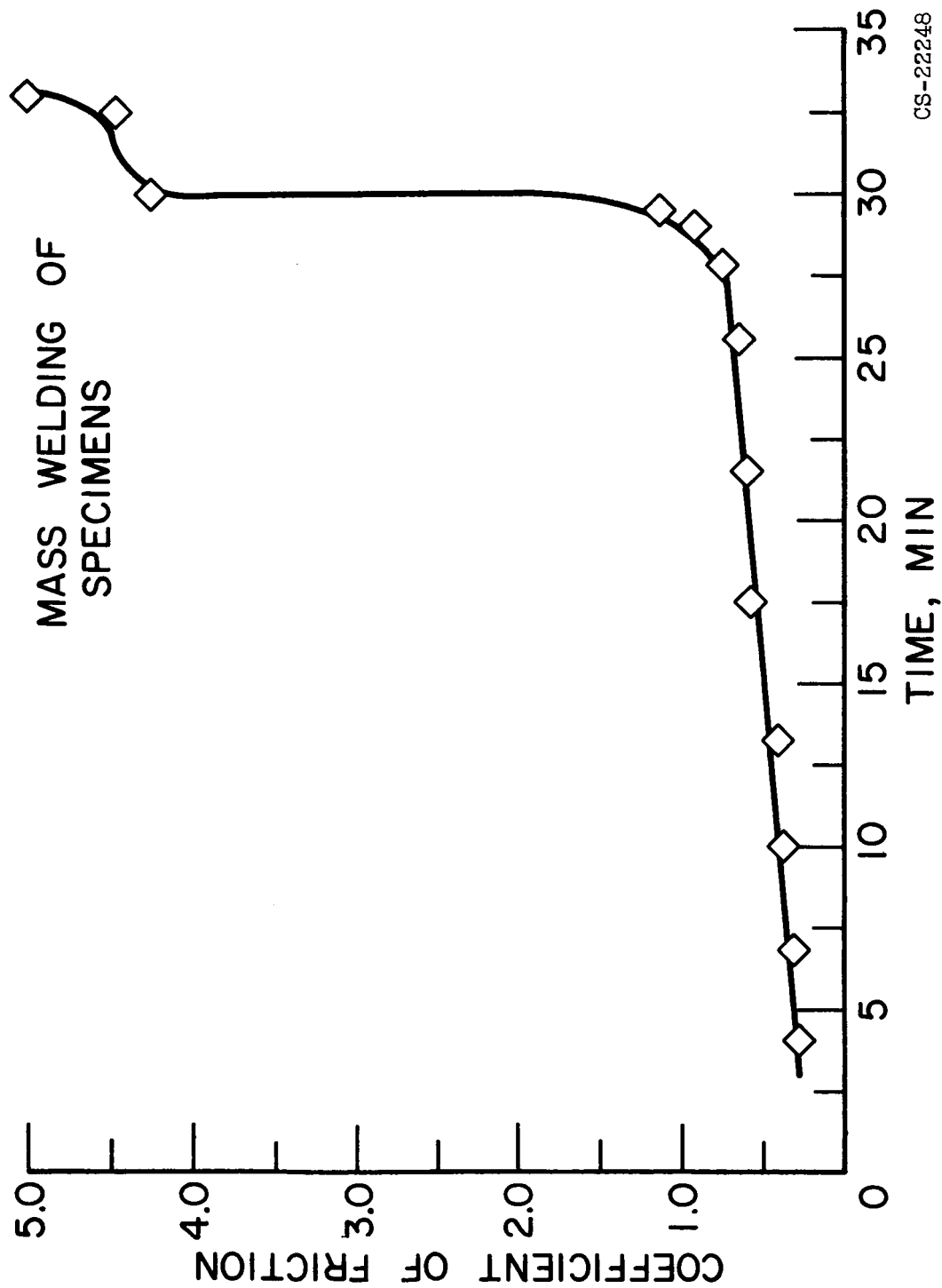
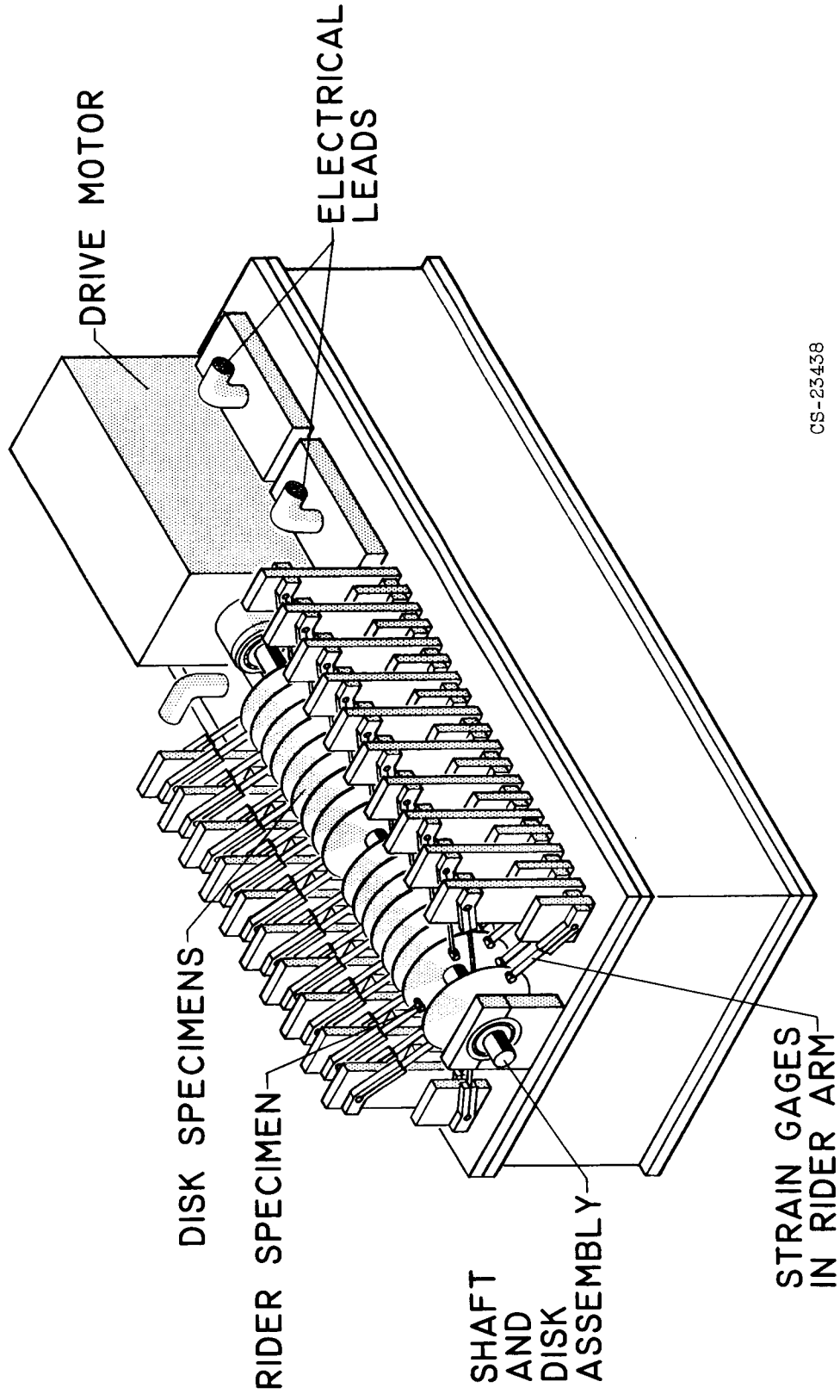


Figure 12. - Coefficient of friction for 52100 sliding on 52100 in vacuum with liquid helium pumping at 2.0×10^{-7} mm Hg. Sliding velocity, 390 ft/min; load, 1000 g.



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Figure 13. - JPL Ranger friction experiment.

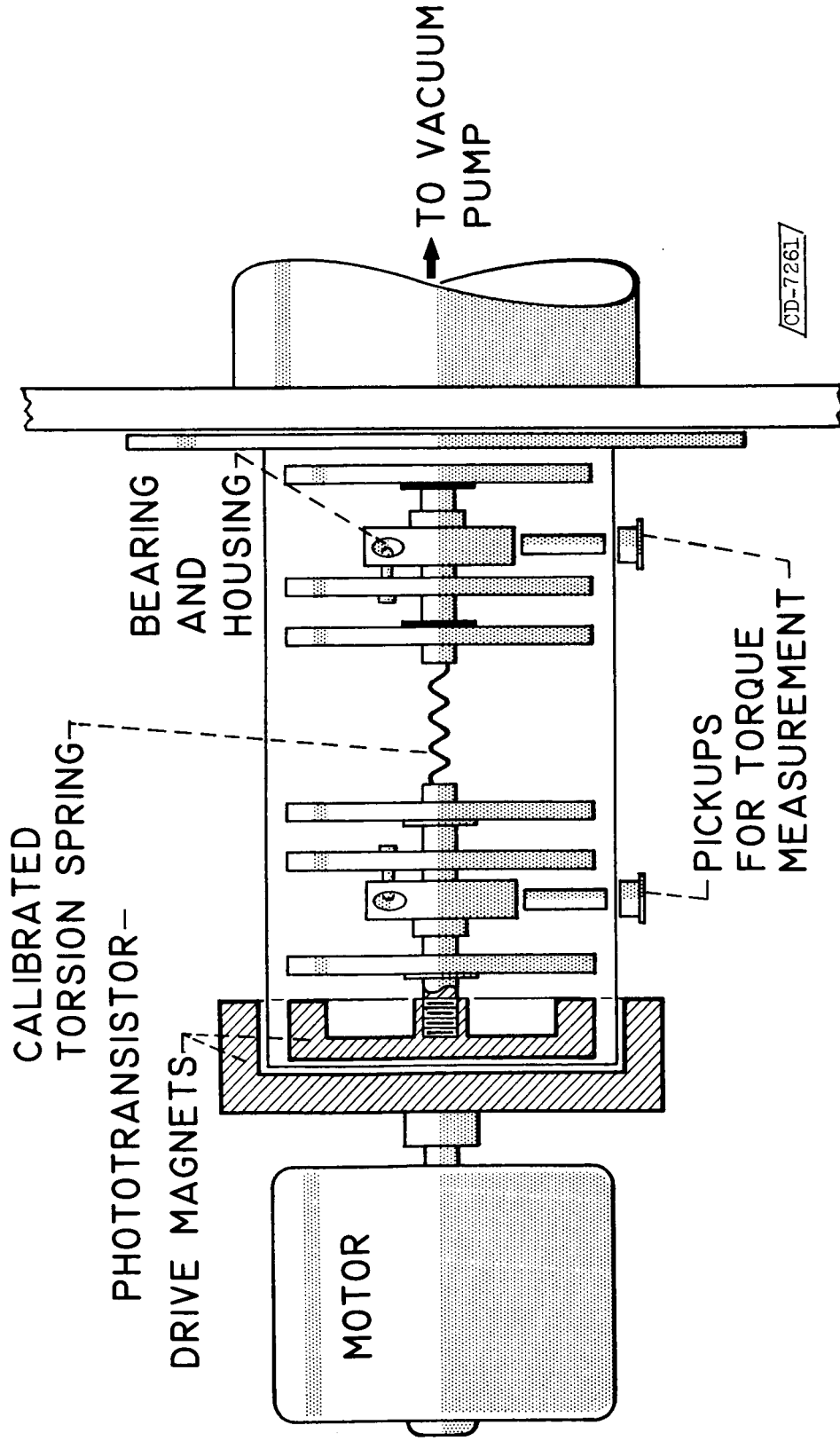


Figure 14. - NASA Marshall Space Flight Center bearing apparatus.

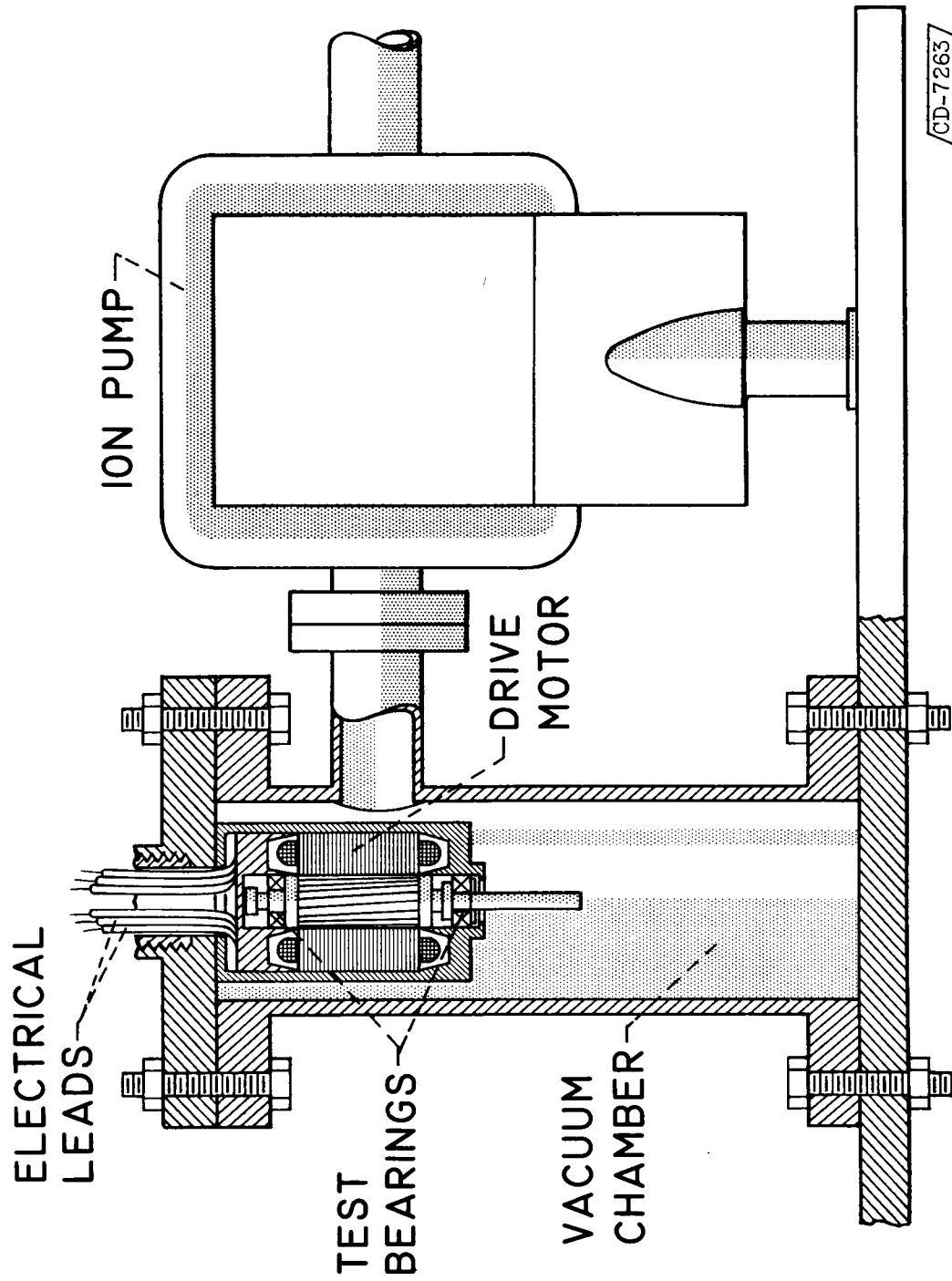


Figure 15. - Goddard Space Flight Center bearing apparatus.